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133 Characterisation of Iceberg Pits on the Grand Banks of Newfoundland

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CHARACTERISATION OF ICEBERG PITS ON THE GRAND BANKS OF NEWFOUNDLAND

Susan H. Davidson[1] and Alvin Simms[2]

[1]Sea Science
200 - 1300 Richards Street
Vancouver, British Columbia
V6B 3G6

[2]Department of Geography
Memorial University of Newfoundland
St. John's, Newfoundland
A1B 3X9

Scientific Authority: Philip Clark
Petro-Canada

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EXECUTIVE SUMMARY

Numerous studies of the eastern Canadian continental shelves have indicated the presence of seabed features formed through iceberg impact processes. These features range from long, shallow scour furrows many kilometres in length to circular or elliptical pits or craters incised into the seabed. Both scour furrows and iceberg pits have been observed on the seabed over the entire eastern Canadian shelf, from Baffin Bay to the Scotian shelf in water depths up to and exceeding 700 m.

Exploration and development of Canada's offshore hydrocarbon resources generally requires the use of bottom-founded structures, for which iceberg scouring and pitting of the seabed must be factored into the engineering design process. Previous studies have focused on furrow-type scours rather than on iceberg pit features, although the relative depth of iceberg pits indicates that the processes leading to pit formation should also be understood in assessing the risk to seabed facilities.

The study described in this report was developed to address some of the issues related to iceberg pits on the Grand Banks of Newfoundland. The purpose of this study was to examine the characteristics of iceberg pits on the Grand Banks, and to develop an overall framework for the assessment of risk to seabed facilities from the iceberg pitting process.

Information on iceberg pits, their locations and observed physical characteristics was obtained from the Grand Banks Scour Catalogue (GBSC), a digital database of seabed ice-contact features previously developed by the Geological Survey of Canada from a variety of data sources. A detailed review of the GBSC has indicated several limitations, including inconsistency in the methods used to identify ice-contact features, exclusion of some features from the database based on the assumption that they represent relict features, inconsistencies in data formats, much missing data, duplicate database entries and incorrect classification of features as pits or scours. Considerable effort was devoted during this project to both upgrading the GBSC and to completion of the associated navigation database.

The available iceberg pit data indicate that the majority of iceberg pits have been found in three main areas: northeastern Grand Bank, Downing Basin and the southern portion of Avalon Channel. These pits are primarily associated with the wellsite surveys contained in the 1984 update to the Mobil Ice Scour Catalogue, and tend to occur in deeper waters. Very few pits have been observed in the shallower water regions on the bank tops, although data coverage of these areas is also limited. Based on limited data, the median crater depth was found to be 2.0 m.

A database of environmental parameters has been developed specifically for this project, focusing on those factors thought to potentially influence the formation, characteristics

and persistence of iceberg craters on the seabed. The environmental database includes regional data on variations in water depth, tidal amplitude, current speed and direction, wave conditions, surficial sediments, seabed mobility and iceberg occurrence.

The relationships between the various environmental parameters and the spatial occurrence of iceberg craters on the seabed have been examined through the use of geographic information systems technology coupled with data-based knowledge acquisition techniques. The empirical rules relating iceberg pit occurrence to the various environmental parameters have shown that water depth is the most important predictor of the presence of iceberg pits on the seabed. Secondary predictors include tidal amplitude, iceberg density, sediment grain size and wave height. Several other parameters (e.g., sediment transport rate, surficial geologic unit) are strongly linked to water depth and thus do not play an independent role in the prediction of the occurrence of iceberg pits on the seabed.

The empirical rules developed from the available data have been used to estimate the probability of observing iceberg pits on the seabed in regions that have not yet been surveyed. This project has been relatively successful in describing the regional characteristics of the existing iceberg pit population and the probability of observing an iceberg pit on the seabed, however, several outstanding issues need further efforts before an accurate risk assessment can be completed. Currently, information is limited with respect to the physical dimensions of the existing iceberg crater population, the separation of recent and relict iceberg scour features, the age distribution of the modern iceberg crater population and the effects of seabed mobility on the persistence and dimensions of ice scour features.

It is recommended that future work related to the risks associated with iceberg pitting of the seabed focus on these areas:

- a thorough evaluation of the ice scour identification and measurement process;
- redesign of the Grand Banks Scour Catalogue and associated navigation database to facilitate their future use;
- further statistical analyses of the existing data;
- refinement of the environmental database for the most significant predictor variables;
- evaluation of the effects of seabed mobility;
- examination of the regional variations in iceberg dimensions;
- development of numerical models of the iceberg pitting process; and
- separation of the observed iceberg pit population into recent and relict features and determination of the age distribution of the recent iceberg pit population.

RÉSUMÉ

De nombreuses études des plates-formes continentales de l'Est du Canada ont révélé la présence, sur le fond marin, d'entités formées sous l'impact des icebergs. Ces entités ont plusieurs formes; certaines se présentent comme des sillons peu profonds et longs de plusieurs kilomètres, d'autres comme des cavités ou cratères circulaires ou elliptiques creusés dans le fond marin. Ces deux types de marques d'érosion ont été observés sur toute l'étendue de la plate-forme continentale de l'Est du Canada, depuis la baie de Baffin jusqu'à la Plate-forme Néo-Écossaise, par des profondeurs d'eau de 700 m et plus.

La recherche et l'exploitation des hydrocarbures au large des côtes canadiennes s'effectuent généralement au moyen de structures qui reposent sur le fond marin et dont la conception doit tenir compte des contacts entre les icebergs et le fond marin. Les études effectuées jusqu'à maintenant ont surtout porté sur les sillons d'affouillement, mais à en juger par la profondeur relative des cavités d'iceberg, il est nécessaire de comprendre également le processus de formation de ces cratères pour bien évaluer le risque qu'il présente pour les structures reposant sur le fond marin.

L'étude dont il est rendu compte dans ce rapport aborde quelques-unes des questions que soulèvent les cavités d'iceberg sur les Grands Bancs de Terre-Neuve. Elle a pour but d'examiner les caractéristiques des cavités d'iceberg sur les Grands Bancs et d'établir une cadre général pour l'évaluation des risques qu'elles présentent pour les ouvrages sous-marins.

L'information sur les cavités d'iceberg, leurs positions et leur morphologie est tirée du catalogue des marques d'affouillement des Grands Bancs (GBSC); cette base de données numériques sur les entités de contact glaciaire du fond marin a été constituée par la Commission géologique du Canada à partir de diverses sources de données. Un examen détaillé du GBSC a fait ressortir plusieurs lacunes, notamment des différences dans les méthodes d'identification des entités de contact glaciaire, l'exclusion de certaines entités que l'on assimile à des marques reliques, un manque d'uniformité dans le format des données, une bonne quantité de données manquantes, des entrées en double et des entités classées à tort comme des cavités d'iceberg ou des marques d'affouillement. Au cours du projet, des efforts considérables ont été faits pour améliorer le catalogue et compléter la base de données de navigation qui s'y rattache.

Les données disponibles indiquent que la plupart des cavités d'iceberg ont été observées dans trois régions : le Grand Banc du nord-est, le bassin de Downing et la partie sud du chenal d'Avalon. Ces cavités sont principalement associées aux levés des chantiers de forage, dont les données sont contenues dans la version 1984 du catalogue des marques d'affouillement glaciel de Mobil; elles se rencontrent généralement en eaux profondes. Très peu ont été observées à faible profondeur au sommet des bancs, bien que la couverture des données soit également limitée dans ces régions. D'après le peu de données dont on dispose, la profondeur médiane des cratères a été estimée à 2,0 m.

Une base de données sur les paramètres environnementaux a été créée spécialement pour ce projet; elle regroupe essentiellement les facteurs qui pourraient, croit-on, influer sur la formation, les caractéristiques et la persistance des cratères d'iceberg sur le fond marin. Elle comprend des données régionales sur les variations de la profondeur d'eau, de l'amplitude de la marée, de la vitesse et de la direction des courants, de l'état des vagues, des sédiments de surface, de la mobilité du fond marin et de la distribution des icebergs.

Au moyen de systèmes d'information géographique combinés à des techniques d'acquisition de connaissances à partir de données, on a examiné les relations entre les divers paramètres environnementaux et la distribution spatiale des cratères d'iceberg sur le fond marin. En appliquant des règles empiriques qui mettent en relation la distribution des cavités d'iceberg avec les divers paramètres environnementaux, on a constaté que la profondeur d'eau était le prédicteur le plus important de la présence de cavités d'iceberg sur le fond marin. Les variables secondaires sont l'amplitude de la marée, la densité d'icebergs, la granulométrie des sédiments et la hauteur des vagues. Plusieurs autres paramètres (par ex. la vitesse de transport des sédiments, l'unité géologique de surface) sont étroitement liés à la profondeur d'eau et, en conséquence, n'interviennent pas de façon distincte dans la prévision de la présence de cavités d'iceberg sur le fond marin.

Les règles empiriques élaborées à partir des données disponibles ont servi à estimer la probabilité de la présence de cavités d'iceberg sur le fond marin dans des régions qui n'ont pas encore été sondées. Le projet a permis, avec passablement de succès, de décrire les caractéristiques régionales de la population actuelle de cavités d'iceberg et d'estimer les chances d'en observer sur le fond marin. Cependant, plusieurs questions demeurent sans réponse, et il faudra poursuivre les efforts pour être en mesure d'évaluer les risques avec exactitude. Actuellement, les données sont limitées en ce qui concerne les dimensions physiques des critères d'iceberg qui existent déjà, la possibilité de distinguer les marques d'affouillement récentes des marques reliques, la distribution des âges des cratères d'iceberg récents ainsi que les effets de la mobilité du fond marin sur la persistance et les dimensions des marques d'affouillement glaciel.

Les auteurs recommandent que, dans les futures études des risques associés au processus de formation des cavités d'iceberg, l'on se concentre sur les activités suivantes :

- évaluation approfondie des méthodes d'identification et de mesure des affouillements glaciels;
- refonte du catalogue des marques d'affouillement des Grands Bancs et de la base de données de navigation qui s'y rattache, pour les rendre plus faciles à utiliser;
- autres analyses statistiques des données existantes;
- affinement de la base de données environnementales en ce qui concerne les prédicteurs les plus significatifs;

- évaluation des effets de la mobilité du fond marin;
- examen des variations régionales des dimensions des icebergs;
- élaboration de modèles numériques du processus de formation des cavités d'iceberg;
- division de la population de cavités d'iceberg observées en entités récentes et entités reliques, et détermination de la distribution des âges des cavités récentes.

1. INTRODUCTION

1.1 Project Background

Numerous studies of the eastern Canadian continental shelves have indicated the presence of distinctive seabed features formed as a result of icebergs impacting the seabed (e.g., Fader and King 1981; Lewis and Barrie 1981). These features range in shape from circular or elliptical pits or craters incised into the seabed to long, shallow furrows many kilometres in length (Figure 1.1). In this report, the terms pit and crater will be used interchangeably to refer to the first type of feature, while the term scour generally refers to the second type of feature, or to the entire population of seabed ice-contact features. Both pit- and furrow-type scour features are often bordered by raised berms composed of the seabed material displaced during the iceberg grounding and scouring process.

Iceberg scour features, including pits, have been observed on the seabed over the entire eastern Canadian shelf, from Baffin Bay to the Scotian Shelf in water depths up to and exceeding 700 m. Previous studies (e.g., Mobil Oil 1985; Lewis et al. 1988) have indicated that the modern population of scour furrows on the Grand Banks of Newfoundland rarely exceeds 1.5 m in depth. On northeastern Grand Bank, the greatest density of scour features (e.g., scours per unit area of seabed) occurs at about 150 m water depth. Iceberg scours on more northerly banks are larger and deeper than those seen on the Grand Banks, and also extend into deeper waters (Clark et al. 1989).

In comparison, iceberg-created pits on the Grand Banks have been found to have an average depth of 3.0 m with a maximum depth of 10.0 m for a pit thought to have been formed within the last few decades (Barrie et al. 1986). It has been estimated that about 3.5% of all iceberg craters on the Grand Banks exceed 5 m in depth (Clark et al. 1986).

Exploration and development of Canada's offshore hydrocarbon resources generally requires the use of bottom-founded structures, for which iceberg scouring and pitting of the seabed must be factored into the engineering design process. The spatial distribution and frequency of iceberg scouring and pitting events together with the dimensions of the resulting seabed features need to be assessed and understood.

Previous studies (e.g., Lewis and Parrott 1987) have examined the frequency of iceberg scouring events on the continental shelves of eastern Canada. These studies have focused on furrow-type scours rather than on iceberg pit features. However, the relative depth of iceberg pits compared to scour furrows indicates that the physical processes leading to pit formation should also be understood in assessing the risk to any equipment or structures buried in the seabed.

Studies of the iceberg pit formation process (e.g., Clark and Landva 1988, Bass and Woodward-Lynas 1988, Bass and Lever 1989, Woodworth-Lynas et al. 1991) have postulated two possible modes for iceberg pit formation. In the first mode, an iceberg drifts onto a shoaling bank, with a scour furrow forming as the iceberg draft exceeds the water depth. As the scouring process continues, soil resistance may increase to the point where the iceberg becomes grounded in one spot. Subsequent oscillatory wave loading on the grounded iceberg causes a bearing capacity failure beneath the berg, together with passive failure of the seabed surrounding the berg. Liquefaction of seabed sediments may play an important role. Progressive soil failure leads to the formation of a pit at the grounding site. The pit gradually deepens until either the buoyancy of the iceberg is enough to reduce the vertical loading on the seabed or some type of ice failure event occurs, freeing the grounded berg from the seabed.

In the second mode of pit formation, a sudden roll of an unstable iceberg results in an increase in iceberg draft, with the iceberg impacting the seabed in a rotational manner. Iceberg instability may result from normal ablation or melting, minor calving events or splitting of a tabular iceberg as observed during the DIGS study (Hodgson et al. 1988). The rotating iceberg digs into the seabed, again causing passive soil failure or seabed liquefaction in front of the berg. Ice failure of the embedded keel may also occur.

Many areas of the Grand Banks of Newfoundland have not been surveyed at all, or the available data have not been analysed for the presence of iceberg pits. The pit creation studies described above suggest that iceberg characteristics, seabed properties and characteristics of the oceanographic environment (e.g., wave and current conditions, water depth) are important factors governing the pit creation process. If the relationships between these environmental factors and the formation, persistence and physical characteristics of iceberg pits were known, the observations from surveyed areas of the banks could potentially be extended to unsurveyed areas. In effect, the knowledge gained from the surveyed areas of the seabed could be extended to the unsurveyed regions.

The study described in this report was developed to address some of the issues related to iceberg pits on the Grand Banks of Newfoundland. The study includes assessment of the spatial distribution and frequency of iceberg pitting events, the characteristics of the iceberg pit population, the relationship between iceberg pit formation and a variety of environmental parameters, and the assessment of risk levels associated with pit formation.

1.2 Project Objectives

The purpose of the study described in this report was to examine the characteristics of iceberg pits on the Grand Banks of Newfoundland, and to provide an overall framework for the assessment of risk to seabed facilities from the iceberg pitting process. Once developed, the various components of the risk assessment framework can be updated or improved as necessary.

This study addressed the following specific objectives:

- To collect and compile into consistent databases the relevant information on iceberg pits, their location and observed physical characteristics, together with the relevant environmental parameters affecting pit formation and persistence on the Grand Banks of Newfoundland.

- To determine the statistical properties of the iceberg pit population.

- To define empirical rules relating the formation, persistence and physical characteristics of iceberg pits to various environmental parameters.

- To estimate the probability of occurrence of iceberg pits of various depths at various locations on the Grand Banks of Newfoundland.

1.3 Technical Approach

This study has used a variety of techniques for data compilation and review, mapping and analysis. These include standard database techniques for data compilation and assessment, statistical analyses using exploratory data analysis (EDA) methodologies, mapping and spatial analyses based on a geographic information system (GIS) approach, and development of empirical rules using data-based knowledge acquisition techniques. The interlinking of these various tools and techniques is shown in Figure 1.2 and summarized in the following material.

Database Development

A database typically consists of many individual records in a digital file, with each record corresponding to a single item (i.e., a single iceberg pit). Each record is sub-divided into pre-defined fields, where each field describes a given characteristic of the record item (i.e., pit depth, width, etc.). In a spatial database such as those used in this study, each record contains fields with location parameters (latitude and longitude or North and East coordinates). Three types of databases have been developed and/or used in this project: two are associated with the iceberg pit data and one with the environmental parameter data sets.

The Grand Banks Scour Catalogue (Canadian Seabed Research Ltd. 1992) has been used as a source of iceberg pit information in this study. This database consists of a compilation of iceberg scour and pit data from several sources, and contains information on feature location, dimensions, survey instrumentation and data quality. An associated database containing navigation data (NAVBASE) is also required in order to define the area of the seabed covered by each individual survey. These databases are fully described in Section 2.0 of this report.

The environmental factors thought to affect pit formation and characteristics have been compiled into a series of database files, again with data from a variety of sources. Environmental factor data can be sub-divided into oceanographic parameters, seabed characteristics and iceberg information. These databases and the associated data sources are discussed in Section 4.0.

Exploratory Data Analyses

Statistical analyses of the iceberg scour population are described by NORDCO Ltd. (1982 and 1984), and Geonautics (1989). These studies used standard statistical analysis techniques, including descriptive parameters such as the mean and standard deviation, frequency distributions and bivariate plots. Results have shown that iceberg scour parameters generally have skewed or long-tailed distributions (Simms 1993), as compared with normal or Gaussian distributions where data are equally distributed on either side of the mean value.

Exploratory data analysis techniques (EDA) have been shown to be more appropriate for the evaluation of skewed distributions (Cox and Jones 1981). EDA parameters include median and quartile-based measures, and allow easy definition and comparison of extreme values. Simms (1993) has shown the value of EDA parameters in assessing the characteristics of the regional ice scour databases on the Baffin Island Shelf, the Labrador Shelf and the Grand Banks of Newfoundland. Section 3.0 describes the EDA approach and the results of the EDA analyses of the iceberg pit database.

Geographic Information Systems

Geographic information systems (GIS) are computer-based mapping and map analysis tools. GIS provide a tool whereby spatial data can be integrated, scaled and manipulated. Spatial data can be displayed as maps, the digital maps can be treated as variables, and the map variables can then be manipulated in logical, statistical and mathematical operations (Simms 1993). GIS procedures also allow the integration and comparison of different types of spatial data such as points (iceberg pits) and polygons (e.g. seabed geology). The incorporation of the iceberg pit database, the navigation database, and the environmental factor databases into the iceberg pit GIS are described in Section 5.0 of this report.

Data-based Knowledge Acquisition

The characteristics of the iceberg pit population and the relevant environmental factors vary spatially over the extent of the study area. The relationships between the environmental parameters and the iceberg pit population must be "extracted" from the spatial database, using a combination of GIS and expert systems approaches. Inductive modelling is used to produce rules describing the relationships between the various parameters of interest; classification tree methods are used to subdivide the multivariate data set (environmental factors) into mutually exclusive, exhaustive subsets which best describe the dependent variable (iceberg pit characteristics) (Simms 1993). Section 6.0 details the approach and results of this methodology.

Risk Assessment for Iceberg Craters

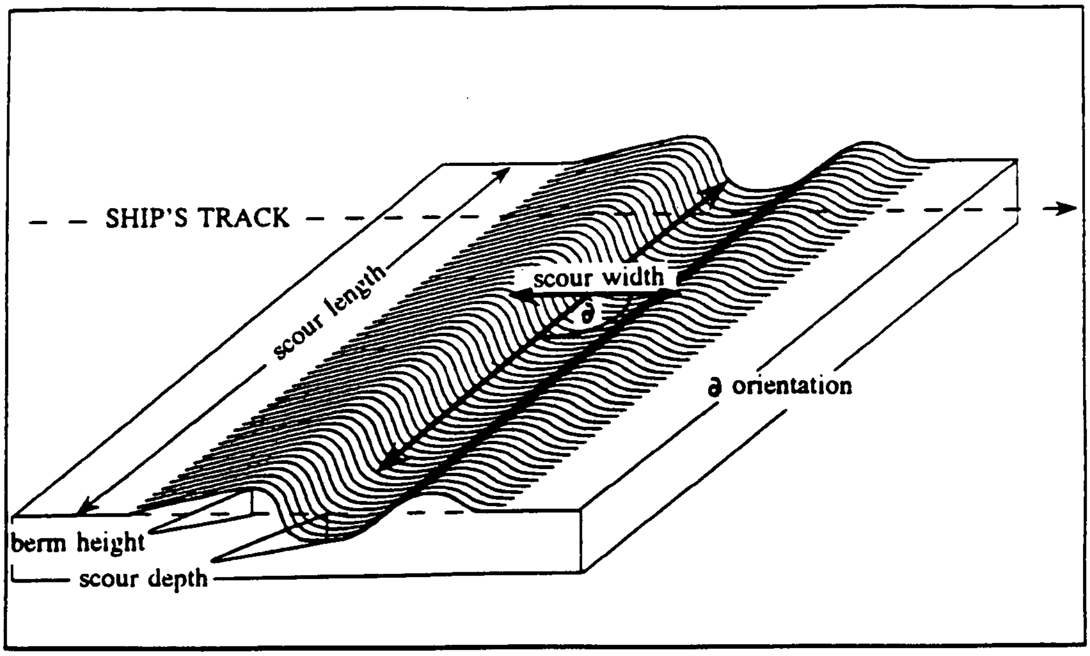
The process used to integrate the results of the previous analyses of the iceberg pit population and the related environmental parameters into a risk assessment for iceberg pits is described in Section 7.0 of this report.

Important Issues

Pit age is an important factor in the assessment of the frequency of pit formation and thus the risk to seabed structures. Observed pit populations are thought to include both modern and relict features, although it is generally assumed, based on the draft limitations of modern-day icebergs, that any scour or pit feature occurring below 200 m water depth is relict. Pits occurring above 110 m have previously been considered to represent the modern, post-glacial population, while pits between 110 m and 200 m have been assumed to represent a mixture of modern and relict features.

As pits age, some degree of degradation and infilling of the pit is likely to occur. Infilling of a pit will cause the measured pit depth to be less than the actual maximum depth at the time of pit formation and may even lead to complete obliteration of shallow pits in regions of active sediment transport. The time frame over which significant infilling and the associated degradation of pit features occurs is again an important parameter.

The issues of relict versus recent features and the infilling of iceberg pits are themes that recur throughout this report. Various data analysis techniques have been used to address these issues, within the limits of the statistical methods used in this study. Recommendations for further research work into these topics are presented in Section 8.0.



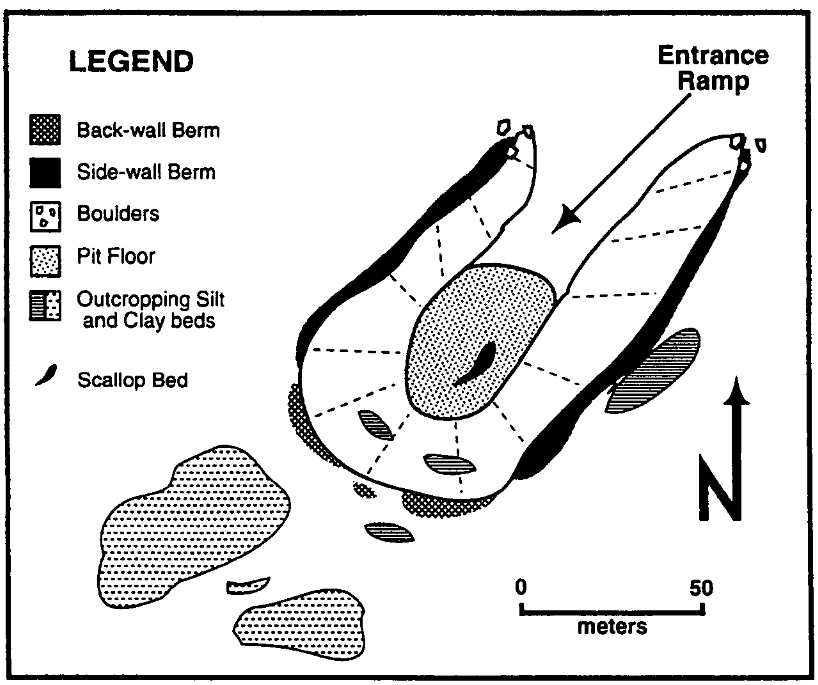


Figure 1.1 Iceberg scour morphologies. Top: generalized morphology for an iceberg scour furrow (from Simms 1993). Bottom: plan view of Bowers Pit (from Barrie et al. 1986).

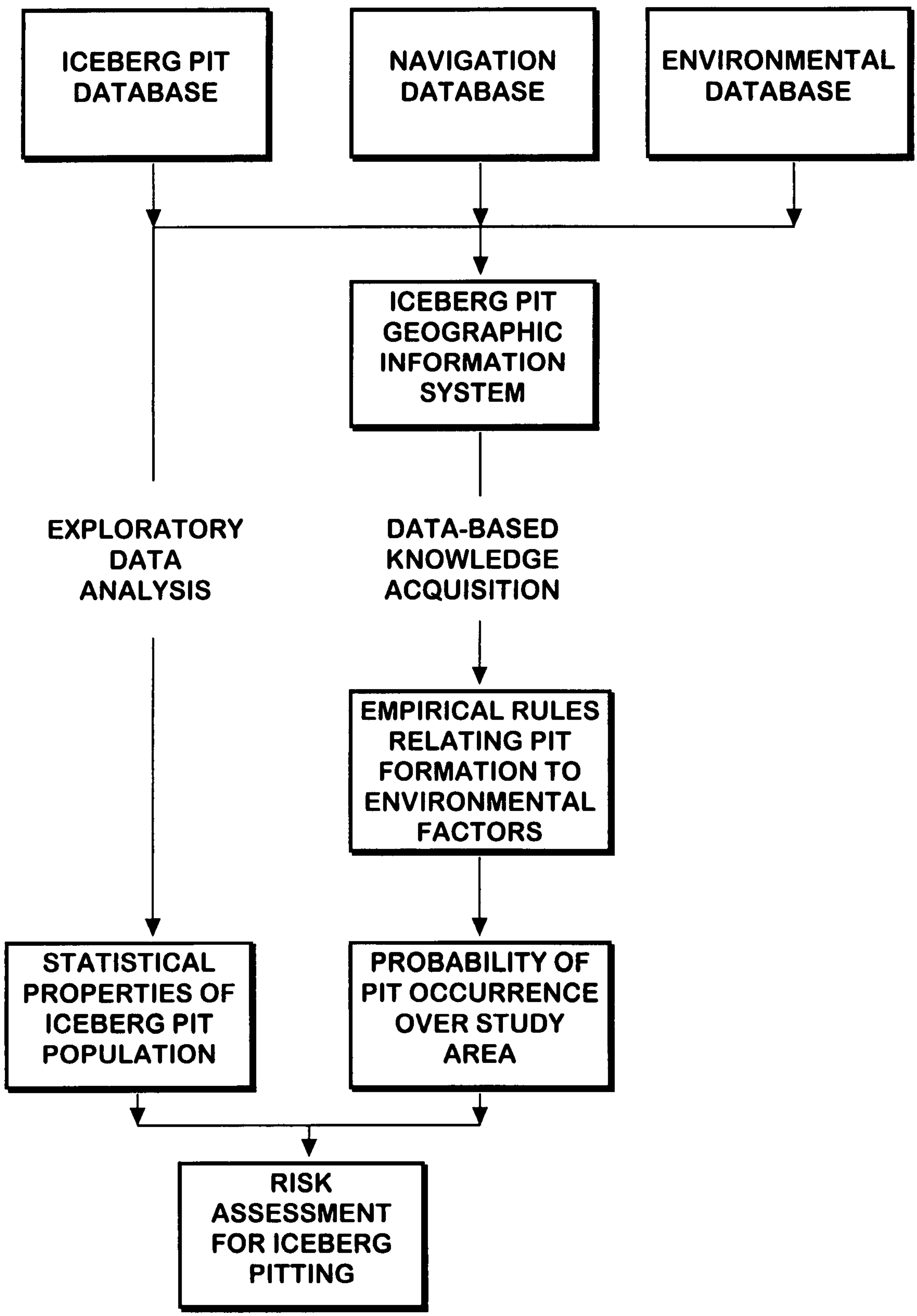


Figure 1.2 Project methodology.

2. ICEBERG SCOUR DATABASES

2.1 The Grand Banks Scour Catalogue

The iceberg pit data used in this project have been derived from the Grand Banks Scour Catalogue (GBSC), a digital database of seabed ice-contact features compiled by Canadian Seabed Research Ltd. (1992). The GBSC has been developed under funding from the Geological Survey of Canada, and includes detailed information on individual ice-contact features found on the Grand Banks of Newfoundland (Figure 2.1). Each seabed feature is included in the database as a separate record; the various fields contain a range of descriptive parameters (Section 2.2.1).

The Grand Banks Scour Catalogue represents a compilation of information from six independent data sources:

- the Mobil Ice Scour Catalogue (NORDCO Ltd. 1982 and 1984);
- the ESRF Repetitive Mapping Ice Scour Catalogue (Geonautics Ltd. 1990 and 1991);
- the AGC Cruise 89-006 Database;
- eight post-1983 AGC cruises (Canadian Seabed Research Ltd. 1992);
- a review of twenty-one post-1983 wellsite survey reports (Canadian Seabed Research Ltd. 1992); and
- a mosaic of the Hibernia Gravity Base Structure (GBS) site (King 1990 and Canadian Seabed Research Ltd. 1992).

Of these six data sources, the first three (the Mobil Ice Scour Catalogue, ESRF Repetitive Mapping Ice Scour Catalogue and the AGC Cruise 89-006 Database) represent pre-existing digital databases of ice-contact features. The analysis techniques used to interpret the raw geophysical data, the corrections applied to the data and the formats of the resulting databases vary between the individual databases. In order to incorporate the pre-existing databases into the Grand Banks Scour Catalogue, field formats were modified to match those used in the GBSC (see Canadian Seabed Research Ltd. 1992). The raw geophysical data records and data analysis and correction techniques were not reviewed as part of the GBSC compilation process.

Ice-contact feature information from the remaining three data sources (post-1983 AGC cruises, post-1983 wellsite survey reports and the GBS site mosaic) had not been compiled into database format prior to the development of the GBSC. For the post-1983

AGC cruises and the GBS site mosaic, ice-contact feature measurements were taken directly from the raw geophysical records and entered into GBSC database format. Seabed feature information obtained from the post-1983 wellsite surveys was taken from the wellsite survey reports rather than directly from the geophysical records (Canadian Seabed Research Ltd. 1992).

In addition to the differences in data analysis and database compilation techniques, the various data sources also differ in the methods used to collect the original geophysical data. Survey design, types of equipment deployed and equipment settings vary significantly between the data sources as well as between the individual surveys contained within each data source. All of these factors affect the accuracy at which ice-contact features have been detected and mapped and have led to substantial discrepancies between data sources.

In this project, the Grand Banks Scour Catalogue was used to represent the population of seabed ice-contact features on the Grand Banks of Newfoundland. The GBSC was then used to determine the relationships between iceberg pits and a variety of environmental parameters, and as a basis for assessing the risk to seabed facilities from the processes that lead to iceberg pitting of the seabed. In order to effectively use the GBSC for these purposes, it is necessary to understand the characteristics and limitations of each data source, and to evaluate the errors involved in feature identification and measurement of feature position and dimensions.

The following discussion focuses on the important characteristics and limitations of each of the six data sources contained within the GBSC. This information is summarized in Tables 2.1, 2.2, and 2.3, with the corresponding survey areas shown in Figures 2.2, 2.3 and 2.4. Tables 2.4 and 2.9 list the number of pit and scour features by data source, for both the original version of the Grand Banks Scour Catalogue and the revised version developed during this project.

It should be noted that much of the information presented in this chapter was not available through any of the various database reports, but rather was compiled as part of the current project. At times, important information was either missing or had to be indirectly inferred from detailed examination of related parameters in the database. In some cases, assumptions had to be made in order to use the data; these assumptions will be noted in the following discussion.

2.1.1 Mobil Ice Scour Catalogue

The Mobil Ice Scour Catalogue is a digital database of ice-impact features, originally compiled in 1981 (NORDCO Ltd. 1982) and updated in 1984 to include data from additional seabed surveys (NORDCO Ltd. 1984). The Mobil database covers northeastern Grand Bank, extending northward and eastward to a water depth of roughly 260 m

(Figure 2.2). The database includes information on the dimensions of ice-impact features and on local seabed characteristics in the vicinity of each identified feature.

The Mobil catalogue was developed from two main data sources: regional surveys conducted by the Bedford Institute of Oceanography (BIO) in Nova Scotia and by the Centre for Cold Ocean Resources Engineering (C-CORE) in Newfoundland; and localized wellsite surveys performed mainly by private industry during offshore oil exploration activities. These two types of surveys are quite different in nature. Regional surveys focus on obtaining a generalized picture of the seabed geology and geomorphology over large areas of the sea floor, and represent large-scale mapping efforts. As such, regional surveys generally consist of single, relatively-linear survey lines extending over long distances with large, unmapped areas between track lines.

Conversely, wellsite surveys are designed to accurately map a relatively small region of the sea floor. In order to achieve the desired level of detail, these surveys usually consist of a parallel grid of primary lines with several perpendicular tie lines. Overlap between adjacent lines ensures that seabed coverage is essentially 100% over the survey area. This high degree of seabed coverage permits long features such as iceberg scours to be traced across contiguous survey lines and identified as single rather than multiple features.

Regional surveys are summarized in Table 2.1 and wellsite surveys in Table 2.2 for both the original Mobil database and the 1984 update study. The study area for the Mobil Ice Scour Catalogue is shown in Figure 2.2, along with the regional survey lines for the Mobil database. Wellsite survey boundaries are shown in Figure 2.4.

Regional Surveys

The regional surveys examined for the original Mobil database include the Hudson 80-010 Cruise and the joint AGC/C-CORE Polaris V Cruise II (8000 series survey lines). The Hudson 80-010 Cruise covered a considerable area of the Grand Banks, collecting more than 4400 line km of survey data. Of this total, 2340 line km were within the study area on northeastern Grand Bank and 2210 line km of Huntec DTS data were analysed for seabed ice-contact features. Detailed mosaics at two sites provided an additional 222 line km of survey data (NORDCO Ltd. 1982).

The joint AGC/C-CORE Polaris V Cruise II acquired approximately 1120 line km of regional survey data, plus 205 line km at three detailed mosaic sites. The majority of the 1120 line km represent a series of 20 parallel track lines on northeastern Grand Bank, spaced at 4 km intervals with a typical length of 28 km. This survey also includes the Northern Pipeline Route (Simpkin 1981), extending in a westerly direction from the study area on northeastern Grand Bank towards the Newfoundland coast.

The 1981 Mobil Ice Scour Catalogue also included data from an iceberg scour study entitled *A Side Scan Sonar Study of Iceberg Scours Between Hibernia and Trave/White Rose Wellsites* (Geomarine Associates Ltd. 1980). This study collected approximately 650 line km of data, primarily along 10 parallel lines roughly 70 km in length, spaced 2 km apart and oriented N 70°E. This set of survey lines is known as the 4000 Series. Although the layout of the survey lines (parallel lines over a rectangular seabed area) resembled other wellsite surveys, the line spacing was not adequate to provide full side scan coverage of the seabed over the study region. This survey should therefore be considered as intermediate in nature between a wellsite survey and a regional survey.

The 4000 Series lines were resurveyed in 1990 as part of the ESRF East Coast Repetitive Seafloor Mapping project (Geonautics Ltd. 1990). The ESRF database resulting from the repetitive mapping project will be discussed in Section 2.1.2. Although the original survey of the 4000 Series lines was not analysed for iceberg pits, the GBSC contains 82 unique scours that can be attributed to this data source (c.f. NORDCO Ltd. 1982 Table 6).

The 1984 update to the Mobil Ice Scour Catalogue added data from the Baffin 81-012, Baffin 82-039 and Hudson 83-033 cruises, and from three pipeline route surveys. The Baffin 81-012 cruise focused on northeastern Grand Bank, and included 183 line km in the Mobil study area. Cruise 82-039 covered the central region of Grand Bank, with four roughly parallel survey lines heading in a northeasterly direction. The Hudson 83-033 cruise focused on a relatively small region of northeastern Grand Bank, with one short line segment to the north of Downing Basin.

The update to the Mobil Ice Scour Catalogue included data from three pipeline route surveys: two versions of the southern pipeline route between the Hibernia area and the coast of Newfoundland (Geonautics Ltd. 1984, Simpkin 1981), and the Geonautics d'Appolonia 1992 survey (no reference available) of the region between Avalon Peninsula and Green and Whale Banks. These surveys are not described in the associated database report (NORDCO Ltd. 1984).

Figure 2.2 shows the track plots for all the regional lines used in the Mobil Ice Scour Catalogue. For the original version of the database developed in 1981, it is clear that only data within the study region defined by the polygon shown on this figure were analysed for ice-contact features. However, the spatial extent of the regional survey data analysed for the 1984 catalogue update is unclear. Most of the survey area for the Baffin 82-039 cruise is outside of the Mobil study area. As no pits and only three scour features are attributed to this cruise, it is not clear whether all of the available data were analysed and few ice-contact features observed, or if only limited portions of the cruise data were actually analysed. Although the three pipeline route surveys are also almost totally outside the boundaries of the Mobil study area, it is clear from the numerous features recorded in the database that these survey lines were analysed for both pit and scour features. This subject will be discussed further in Section 2.3 of this report.

Wellsite Surveys

The majority of the ice-contact seabed features in the Mobil Ice Scour Catalogue are associated with wellsite surveys. Wellsite survey areas are clustered together in a relatively small area of northeastern Grand Bank, with the exception of four wellsites in Downing Basin. Wellsite locations are shown in Figure 2.4, with survey information summarized in Table 2.2.

The original NORDCO study examined seventeen wellsite surveys conducted from 1979 through 1982. Iceberg scour furrows were recorded for fourteen wellsites; however, iceberg pits were identified at only four of these sites. Three wellsites (Hibernia South, Mercury and West Flying Foam) showed no evidence at all of any ice-contact features on the seabed. The seventeen wellsite surveys covered roughly 2100 km^2 of seabed, of which 1350 km^2 had Huntec DTS data.

An additional eight wellsite surveys were analysed for the 1984 update to the Mobil Ice Scour Catalogue. All eight surveys indicated the presence of iceberg scours, with iceberg pits found at seven of the eight sites. These surveys are summarized in Table 2.2 and shown in Figure 2.4.

Geophysical Data Acquisition and Analysis

The Mobil catalogue was originally developed in order to address the potential hazard to seabed structures on the Grand Banks of Newfoundland from icebergs impacting the seabed. The catalogue was based on sub-bottom profiler and side scan sonar data, with various instruments used on the different surveys. Tables 2.1 and 2.2 indicate the particular sub-bottom profiler and side scan sonar instruments used on each of the regional and wellsite surveys examined for the Mobil database.

In addition to variations in instruments and survey techniques, the methods used for ice-contact feature recognition differed considerably between the various portions of the Mobil database. In the original Mobil catalogue, iceberg pits and scours were recorded only when seen on the Huntec DTS data for the regional survey lines. The associated side scan sonar records were used simply to confirm the nature of the individual feature (NORDCO Ltd. 1982).

For the wellsite surveys, examination of the various parameters in the Grand Banks Scour Catalogue has shown that iceberg pits were recorded only when seen on the sub-bottom profiler (Huntec DTS or ORE 3.5 kHz) records. Consequently, all pits in this portion of the Mobil database have depth values greater than zero. Iceberg scours appear to have been recorded when observed either on sub-bottom profiler or side scan sonar data for these wellsite surveys.

In the 1984 update to the Mobil Ice Scour Catalogue, both iceberg scours and pits appear to have been recorded when seen on either the side scan sonar or the sub-bottom profiler records for the regional survey lines, the pipeline surveys and for the wellsite surveys. Table 2.3 summarizes the feature recognition methods used in each portion of the Mobil database and the remainder of the GBSC.

It should be noted that sub-bottom profiler systems are designed to provide a vertical profile of the seabed rather than a plan view of the sea floor as for side scan sonar systems. As such, sub-bottom profilers insonify a very narrow swath of seabed compared to side scan sonar systems. This difference has important implications in the calculation of spatial frequencies of iceberg pitting or scouring (features per square kilometre) and will be discussed in more detail later in this report.

The Mobil ice scour catalogue includes only "fresh-looking" scours, features easily recognizable as scours and well-defined on side scan sonar and sub-bottom profiler records. These scours are believed to have formed at some point since the last low-stand of sea level (see Section 4.3.1) and thus represent the "modern" ice scour population (NORDCO Ltd. 1984). The topic of modern compared to relict ice contact features is discussed in more detail later in this report.

Although only modern-looking iceberg scours were included in the Mobil catalogue, it appears that no differentiation was made between relict and recent iceberg pit features, possibly due to difficulties in determining pit age. The database does not distinguish between crater chains and individual crater features, nor have buried notches, pockmarks and partially buried (mottled) iceberg scours been included in the catalogue.

The Mobil database contains information on feature location, dimensions and orientation. Dimensions are limited to depth and sometimes width for those features identified and measured only from sub-bottom profiler records (primarily pits - see above). Widths were corrected for aspect-ratio distortions only when feature orientations were measured from side scan sonar records. Once incorporated into digital format, feature locations were plotted against survey maps and track plots to identify position errors.

In addition to dimensions and locations of seabed ice-contact features, the Mobil catalogue contains information on water depth at the feature location, surficial geology, sediment thickness and the presence or absence of sedimentary bedforms.

2.1.2 ESRF Repetitive Mapping Ice Scour Catalogue

The 4000 Series lines were first surveyed in 1979 by McElhanney Surveying and Engineering Ltd. and Geomarine Associates Ltd. (Geomarine Ltd. 1980). The main goal of this study was to document the character and distribution of iceberg scours in the

Hibernia development area. Scours were mapped from side scan sonar data and included in the Mobil Ice Scour Catalogue. Iceberg pits were not mapped during the 1979 study.

The frequency of new scour formation and rates of scour degradation and infilling are important parameters in the assessment of risk to seabed structures from iceberg impact and seabed scouring. One method that can be used to estimate these parameters is to resurvey a previously mapped area and to compare the two resulting data sets. After an initial feasibility study conducted by the Atlantic Geoscience Centre, the Environmental Studies Research Funds chose the 4000 Series lines for resurvey in 1990 (Geonautics Ltd. 1990). Details of the 4000 Series surveys are given in Table 2.1, with track lines shown in Figure 2.3.

Geophysical Data Acquisition and Analysis

The original 4000 Series side scan sonar survey was performed using an ORE 100 kHz side scan sonar connected to an EPC 3200 dual channel recorder system. The same system was used for the 1990 resurvey, while duplicating the original operating conditions and survey tracks as closely as possible. The Huntec DTS sub-bottom profiler, 10 cubic inch airgun, Klein 50 kHz side scan sonar and Raytheon 12 kHz echo sounder were also deployed during the resurvey of the 4000 Series lines.

The data analyses performed during the ESRF study focused primarily on a detailed comparison of the ORE side scan data collected in 1979 and 1990. The dimensions of seabed ice-contact features, changes to previously-mapped features and any new features were documented and compiled into database format. A comparison of the two surveys indicated significant differences in measured scour dimensions for the remapped scours, although qualitative comparisons showed no observable changes (Geonautics Ltd. 1991).

Of the 43 scours mapped by Geomarine Associates in 1979, 30 were remapped in 1990 (Geonautics Ltd. 1991). The remaining 13 scours were missed due to slight differences in the survey track lines. Two potentially "new" iceberg pit features were identified: one appears clearly as a crater chain on the reproduced side scan record, while the second feature consists of four closely spaced, but perhaps independently-formed, craters. It should be noted that the Grand Banks Scour Catalogue currently contains 82 scour records attributed to the original survey of the 4000 Series lines, while the report describing the original Mobil Ice Scour Catalogue (NORDCO Ltd. 1982) lists 77 features from this source.

Although the ESRF project focused on a comparison of the two sets of ORE side scan sonar records, the Huntec DTS and Klein 50 kHz side scan sonar also provided important information on the characteristics of ice-contact features in the study area. The Huntec DTS sub-bottom profiler data provided scour depths, profile shapes and berm dimensions, while the Klein 50 kHz sonograms provided a relatively high-quality, high-resolution side scan data set. The Klein data revealed the presence of many additional seabed ice-contact features not visible on the ORE data sets. As a separate project (Geonautics Ltd. 1990), these additional data sources were compiled into an expanded scour catalogue, using a format similar to those used previously for the East Coast Regional Ice Scour Database (Geonautics Ltd. 1989) and the Mobil Ice Scour Catalogue (NORDCO Ltd. 1982). This expanded scour database has been named the ESRF Repetitive Mapping Ice Scour Catalogue.

The ESRF Repetitive Mapping Ice Scour Catalogue includes information on seabed ice-contact features on a feature-by-feature basis. The catalogue includes all features noted on the side scan records, with no distinction between recent and relict features except in the comment section of the database. The catalogue includes 280 separate ice-contact features, of which 264 have been identified as iceberg scours and 16 as iceberg pits. Crater chains have not been separately identified, although "overlapping crater chains" or "ribbed scours" are sometimes mentioned in the comment field.

The ESRF catalogue includes information on feature location; feature dimensions (width, length and depth when crossed by ship's track) and orientation, instrumentation and survey details, plan and profile shapes, berm width and height, data quality and local seabed geology. Arcuate and sinuous scours have been classified as a series of two or more relatively straight segments, with each segment as a separate record in the database.

Raw measurements were obtained from the geophysical records by a single, experienced interpreter in order to maintain consistency in feature identification. The raw measurements were then compiled into ASCII digital format, visually checked for errors and processed to correct scour dimensions for aspect-ratio distortions. The corrected measurements were then checked for extreme values and compared manually against a random sampling of ten scours.

2.1.3 AGC Cruise 89-006 Database

The AGC Cruise 89-006 Database was compiled by Geonautics Ltd. in a similar manner to the ESRF Repetitive Mapping Ice Scour Catalogue (Canadian Seabed Research Ltd. 1992). Although no report was available for that project, the following information has been compiled from various sources. Details of the Cruise 89-006 Database are given in Table 2.1, with survey track lines shown in Figure 2.3.

Cruise 89-006 collected side scan sonar and sub-bottom profiler data over the northeast Newfoundland Shelf, using the BIO 70 kHz and Klein 100 kHz side scan sonar systems, and the Huntec DTS sub-bottom profiler. Ice-contact features were observed primarily on the BIO 70 kHz side scan records. The AGC Cruise 89-006 Database contains 188 unique ice-contact features, of which 77 have been classified as iceberg pits and 111 as scours. Crater chains are not mentioned. The majority (74 of 77) of the iceberg pits recorded in this database were not crossed by the sub-bottom profiler system; thus pit depths are not generally available.

In water depths less than 110 m, the AGC Cruise 89-006 Database includes all observed iceberg scour features. In deeper water, only those features judged to be relatively recent have been included in the database. Features were identified as recent based on clarity and cross-cutting relationships where possible. It is not known if the same criteria were applied to craters as to scour furrows.

2.1.4 Post-1983 AGC Cruises

In addition to previously compiled digital databases, the Grand Banks Scour Catalogue contains new scour measurements from eight regional surveys conducted by the Atlantic Geoscience Centre (Canadian Seabed Research Ltd. 1992). Side scan sonar and sub-bottom profiler data from all or parts of the cruises listed in Table 2.1 were examined.

The eight cruises cover the time period from 1984 through 1990, although each survey covered a different portion of the northeastern continental shelf. Survey details are summarized in Table 2.1 for each of the above cruises with survey track lines shown in Figure 2.3.

Geophysical Data Acquisition and Analysis

With the exception of cruise 85-057, all of the post-1983 AGC surveys analysed by Canadian Seabed Research Ltd. (1992) utilized the Huntec DTS sub-bottom profiler system and two side scan sonar systems deployed simultaneously. In a typical survey, the BIO 70 kHz side scan sonar was operated at a range of 750 m per channel and the higher resolution Klein 100 kHz system was operated at a range of 250 m per channel.

Limited regional survey data were collected during cruise 85-057. The primary focus of this cruise was to conduct submersible observations and detailed sampling of selected seabed sites; regional surveys were performed only when weather conditions prohibited other operations. The Klein 100 kHz side scan sonar system was used together with a 3.5 kHz sub-bottom profiler system.

The side scan sonar records collected during the post-1983 AGC surveys were analysed for recent seabed ice-contact features, where recent features were defined to include all observed features in water depths less than 110 m, and those appearing "sharp or fresh" on the side scan records in water depths greater than 110 m (Canadian Seabed Research Ltd. 1992). When two sets of side scan sonar data were available, both sets were used to identify ice-contact features although feature measurements were taken from a single data source. Overlapping areas covered by more than one survey were analysed only once for ice-contact features; areas already covered by the Mobil Ice Scour Catalogue, the ESRF Repetitive Mapping Catalogue and the AGC Cruise 89-006 Database were also avoided.

The Grand Banks Scour Catalogue contains 1114 separate ice-contact features from the eight post-1983 AGC surveys. Of this total, 141 represent individual iceberg pits and 902 represent iceberg scours. An additional 50 scours occur in association with one or more craters, and 18 crater chains composed of 52 individual craters were identified. Three additional features have been described as overlapping crater chains, where a single feature appears to consist of several linked craters.

The portion of the Grand Banks Scour Catalogue developed from the post-1983 AGC surveys contains information on feature location, dimensions and orientation, survey and instrumentation details, plan and profile shapes for each individual feature, berm height, data quality and local seabed geology. As for the ESRF Repetitive Mapping Ice Scour Catalogue and the AGC Cruise 89-006 Database, individual features are recorded as one or more segments, with each segment representing a significant change in feature characteristics such as orientation or width (Canadian Seabed Research Ltd. 1992). Conversely, the Mobil Ice Scour Catalogue contains a single record for each scour or pit feature. This portion of the GBSC also records crater chains and iceberg pits that occur in association with scours as single, multi-segmented features.

Identification and measurement of iceberg pits and scours were performed by two interpreters, working independently but cross-checking in the case of questionable features. Once the raw measurements were entered into digital database format, the data were processed to yield UTM coordinates for the feature and to correct the dimensions and orientation for aspect-ratio distortions. The database was checked for extreme values in feature dimensions, orientation and location; extreme values were verified against the original data coding sheets. Further quality control measures included checks between interrelated database fields and a visual comparison of 2% of the records with the original interpreter coding sheets (Canadian Seabed Research Ltd. 1992).

2.1.5 Post-1983 Wellsite Surveys

Twenty-one wellsite survey reports were reviewed by Canadian Seabed Research Ltd. (1992) as part of the Grand Banks Scour Catalogue compilation project. These reports represent all wellsite survey reports submitted to the Canada-Newfoundland Offshore Petroleum Board (CNOPB) and released as of May 1992. No geophysical data records were analysed in this review.

Of the twenty-one wellsite survey reports, only nine contained detailed scour measurement data. Five of the nine surveys were in water depths greater than 140 m, while the remaining four were in water depths less than 110 m. Since none of the deeper water surveys discriminated between relict and modern scours, only the four wellsite surveys in water depths less than 110 m were included in the Grand Banks Scour Catalogue (Canadian Seabed Research Ltd. 1992). A summary of the four wellsite surveys incorporated into the Grand Banks Scour Catalogue is given in Table 2.2, with survey areas shown in Figure 2.4.

The Grand Banks Scour Catalogue contains 47 separate ice-contact features from the five post-1983 wellsite surveys. This total includes seven iceberg pits and forty scours. No mention has been made of crater chains or pits that occur in conjunction with ice scours. Only features visible on the side scan sonar records have been incorporated into the GBSC; an additional seven scours and ten pits visible only on sub-bottom profiler records are mentioned in the wellsite survey reports (Terraquest Associates 1994) but not included in the Grand Banks Scour Catalogue. No depth information has been included for any of the 47 ice-contact features and widths are the only dimension given for the seven iceberg pits. It is not known if the feature dimensions have been corrected for slant-range or aspect ratio distortions. Data quality parameters have not been included in the database.

2.1.6 GBS Site Mosaic

A detailed survey of the Hibernia Gravity Base Structure (GBS) site was performed as part of AGC cruise 87-014. A side scan sonar mosaic was developed for the site by King (1990); the mosaic, together with the raw side scan sonar records, was reviewed for ice-contact features by Canadian Seabed Research Ltd. (1992). Survey details are given in Table 2.1, listed under AGC cruise 87-014.

Six iceberg scours were identified and included in the GBSC from the GBS site mosaic. Depth information was not included in the database for these six scours. No pits were identified at this site.

2.2 Review of the Grand Banks Scour Catalogue

This project represents the first use of the Grand Banks Scour Catalogue for data analysis purposes. Prior to its use, the GBSC was reviewed for completeness, data quality and data reliability. Three aspects of particular importance to this project were included in this review: the relative identification of scour and pit features, the presence of duplicate features in the database and the limitations associated with the measurement of feature dimensions.

2.2.1 Database Structure

As described above, three pre-existing digital databases (the Mobil Ice Scour Catalogue, ESRF Repetitive Mapping Ice Scour Catalogue and the AGC Cruise 89-006 Database) were converted from their original formats to a standardized GBSC format. The format used in the Grand Banks Scour Catalogue is given in Table 2.5; a complete description of the database fields is given in Canadian Seabed Research Ltd. (1992). For the pre-existing databases, only readily-available digital data were compiled into GBSC format.

Examination of the various fields in the GBSC showed that many fields are empty for the data originating from the pre-existing digital databases, particularly for fields pertaining to survey instrumentation. This type of information is required in order to determine both the area of the seabed covered by each survey and the relative reliability of the data contained in the GBSC. Considerable effort was devoted during this project to compiling the survey information summarized in Tables 2.1, 2.2 and 2.3.

The Grand Banks Scour Catalogue, in its present format, is difficult to use for data analysis purposes. Several improvements to the GBSC could be made in order to improve this situation:

- Most of the field values in the GBSC are currently entered as numeric values. For many fields, alphabetic characters would better describe the possible field values and would reduce the need for constantly referring to the GBSC documentation when conducting database queries. As an example, the current codes of 3 and 1 for sand and gravel, respectively, could be replaced by alphabetical codes such as S and G.

- The use of both zero and blank values in some fields (e.g., depth - see Section 2.2.4) led to confusion between when a parameter had been measured and the value was zero, and when no value had been measured. It is recommended that blanks not be used to represent field values other than to indicate missing data.

- There are several inconsistencies in how data are entered in various portions of the database. Again using the depth field as an example, ice-contact features derived from the Mobil Ice Scour Catalogue are given depth values equal to the instrument resolution (0.3, 0.5 or 1.0 m) when the feature was visible on the sub-bottom profiler data but the depth was too small to measure accurately. In other portions of the database (e.g., post-1983 AGC cruises), these types of features are given a depth value of 0 m. Thus, complex database query strategies must be used prior to performing statistical analyses on the meaningful data. It is strongly recommended that consistent data entry strategies be used for the entire database.

- The Mobil Ice Scour Catalogue contains a single record for each ice-contact feature. In the remaining portions of the GBSC (ESRF Repetitive Mapping Ice Scour Catalogue, AGC Cruise 89-006 Database, post-1983 AGC cruises, post-1983 wellsite surveys and the Hibernia GBS site mosaic), the database contains one record for each segment of a multi-segmented feature. Thus, a long scour feature may be represented by as many as 10 records in the database. The multi-segmented format creates several problems for data analysis: the actual number of individual ice-contact features in the GBSC is difficult to determine, the type of feature (scour furrow vs. crater) is sometimes unclear, and parameters such as total scour length and average width are not readily available. These problems are particularly important for any analyses of the scour furrow population. It is recommended that a database be developed with a single record only per individual ice-contact feature.

- The position of each ice-contact feature in the GBSC is given as UTM coordinates only. It is recommended that the original latitude and longitude data for each feature be retained in the GBSC, allowing other coordinate systems or datums to be easily used if desired.

2.2.2 Feature Identification

In this review, two main issues arose with respect to feature identification: when should a seabed feature observed on the geophysical records be included in the ice-contact feature database, and how should pits be differentiated from short scour furrows. The first issue has been examined through the ESRF repetitive mapping program (Geonautics Ltd. 1990) and various interpreter variability assessments. The second issue will be discussed here.

As previously described, many of the iceberg scours included in the GBSC are represented as multi-segmented features, with more than one database record per individual ice-contact feature. In this format, each individual record in the database represents a significant change in at least one scour attribute, most commonly scour orientation (Canadian Seabed Research Ltd. 1992). The multi-segmented format applies primarily to scour furrows rather than crater features. However, in the post-1983 AGC cruise portion of the GBSC, craters found in conjunction with a linear scour furrow are recorded as separate segments of the same overall scour feature.

Although the multi-segmented format has the advantage of more accurately representing the characteristics of long scour features, this format created a problem related to iceberg crater identification with the post-1983 AGC cruise portion of the database. For those features where craters were found in association with a scour furrow (plan shape codes 6, 7 and 8), all segments of each individual ice-contact feature were marked as craters (type code C). Scour segments and crater segments were not uniquely identified. For some of these features, information in the comment field allowed the appropriate segment to be designated as a crater, with the remaining segments redefined as scours (type code S).

For features where no information was provided in the comment field as to which scour segment or segments were actually craters, it was first assumed that there was only one crater segment per scour feature. In order to determine which segment of the scour feature to designate as a crater, the width:length ratios were calculated for all the individual segments. The "roundest" segment was then chosen as the crater segment, where a "round" segment was defined as having a width:length ratio of one. A total of 110 crater segments were redefined as scours through this process. The resulting changes to the Grand Banks Scour Catalogue are given in Table 2.6.

During the assessment of the multi-segmented features in this portion of the GBSC, it became apparent that some of the remaining features may have been incorrectly classified as either craters or scours. Through discussions with Gary Sonnichsen of the Atlantic Geoscience Centre, it was determined that the relative identification of craters and scour furrows was generally based on shape, as directly observed on the side scan sonar records. However, side scan sonar records are usually scale-distorted, in that the along-track scale is different from the across-track scale. Thus, a round feature on the seabed would appear elliptical on the side scan record, while a linear feature may appear rounder on the records than on the seabed, depending on the orientation of the feature relative to the ship's heading. Post-processing for aspect-ratio corrections is required in order to more accurately assess feature shape.

To address this issue, the width:length ratios were calculated and reviewed for every record in the Grand Banks Scour Catalogue. This review was limited by several factors:

- width or length information was missing for many features, particularly pits;
- length information appeared to be incorrect for some features;
- it was usually not clear if the reported scour length represented the total length of the feature or only the length of that portion of the feature visible on the side scan sonar records;
- for multi-segmented features, it is not possible to use width:length ratios to differentiate between a short scour segment and a crater.

Although this review identified features that potentially were incorrectly classified, no additional changes were made to feature type as a result of these limitations. The accuracy of the feature length information will be discussed in Section 2.2.4.

The type identification for one additional feature in the database was changed from scour to crater in response to an enquiry from Petro-Canada to the Atlantic Geoscience Centre (G. Sonnichsen, pers. comm.). A review of the original geophysical data showed that, due to poor side scan coverage of the feature, Scour ID 575 had been incorrectly identified as a scour furrow rather than as a crater. This entry has been corrected in the revised version of the Grand Banks Scour Catalogue.

2.2.3 Duplicate Entries

The issue of duplicate pits in the database is not simple to address, primarily due to the inherent errors in the processes of identifying, dimensioning and locating seabed features from geophysical records. For example, navigation errors can lead to a difference in location of on the order of a few hundred metres for the same feature surveyed on two separate cruises. Thus, if two pits in the database are located within a few hundred metres of each other, they potentially represent duplicate surveys of the same feature rather than two distinct pits.

The feasibility of using pit dimensions to differentiate between two distinct pits and two surveys of the same pit was investigated as part of the review of the Grand Banks Scour Catalogue. For much of the database (those pits originating from the Mobil catalogue) the only pit dimensions given are depth and width. Pit length and orientation values are also available for most of the pits originating from the ESRF Repetitive Mapping Database, the Cruise 89-006 Database and the post-1983 AGC cruises analysed by Canadian Seabed Research Ltd.

The depth value as recorded in the GBSC represents the maximum observed depth from the sub-bottom profiler transect of the pit; this may or may not represent the maximum pit depth, depending on whether or not the deepest part of the pit was crossed by the survey line. Similarly, when pit width was obtained from the sub-bottom profiler record, this width will exceed the actual width unless the profiler track crossed the pit at a right angle. Again, the recorded width does not represent the maximum width unless the pit was crossed at its widest point. Pit widths were recorded from the sub-bottom profiler data for parts of the Mobil database.

It is expected that pit widths measured from side scan sonar records are much more accurate than those measured from sub-bottom profiler data, assuming that the appropriate data corrections have been applied (i.e. slant-range and aspect-ratio distortions). However, if the entire feature was not visible on the side scan record, then the recorded width (and length) may not represent maximum values for that particular feature.

Thus, for those portions of the database where pit dimensions were obtained from the sub-bottom profiler data alone (original Mobil database, including wellsite surveys and regional lines), it is very difficult to eliminate duplicate recordings of the same feature from the database. Where two separate features in the database occur within a few hundred metres of each other and are from separate surveys, a comparison of pit dimensions can not always be used to eliminate duplicate database records. Recorded differences in pit dimensions may represent differences in survey techniques or position of the track line relative to the pit rather than actual physical differences as would be expected for two distinct seabed features.

The problem of differentiating between duplicate features was clearly illustrated when the database was searched for features corresponding to Bowers Pit. Bowers Pit is a well-surveyed iceberg pit located roughly 11 km to the east-southeast of the Hibernia P-15 discovery well. This feature is particularly significant for its observed depth of 10 m (submersible-based measurements), making Bowers Pit the deepest feature included in the Grand Banks Scour Catalogue.

A database search for records representing Bowers Pit was based on identification of all pit features in the GBSC with recorded locations within approximately 500 m on each side of the known location of the pit (UTM coordinates 5176654 N, 681381 E based on NAD 27). This search identified six craters from three separate surveys (three from the Mara wellsite survey, two from cruise 88-108 and one from cruise 90-021); all six potentially represent duplicate database entries for Bowers Pit. These database entries are listed in Table 2.7.

A review of the available side scan sonar data for three of these six features was conducted by Gary Sonnichsen of the Atlantic Geoscience Centre. This review indicated that the two pits identified from cruise 88-108 data likely represented duplicate crossings of Bowers Pit, with the two pits seen on separate survey lines shot in opposite directions. Although the readily available side scan data for cruise 90-021 are of poor quality, they indicate that this pit is probably also Bowers Pit.

Side scan data from the Mara wellsite survey were not readily available. However, the three pits found in the near vicinity of the Bowers Pit location are numbered sequentially in the database, indicating that they probably represent three separate features identified from the same survey line segment. Of these three pits, the deepest has a depth of 7 m and is thought to represent Bowers Pit. The area surrounding Bowers Pit has been well surveyed, and no other deep pits have been found in the area. Variations in measured depth between various surveys of the same feature will be discussed later in this section.

Based on this review, it appears that at least four of these six database entries actually represent the same feature, Bowers Pit. A comparison of the database entries for pit dimensions for each of these four features is shown in Table 2.7.

The first three entries in Table 2.7 have been identified from analysis of side scan data as duplicate records of the same feature (G. Sonnichsen, pers. comm.). The fourth entry probably also represents Bowers Pit (based on extreme depth value). Thus, it would be expected that observed dimensions for the first four features would be relatively similar. However, a comparison of the recorded values shows a wide discrepancy in the depth and width fields, clearly illustrating that pit dimensions cannot easily be used to differentiate between duplicate surveys of the same feature and the presence of two distinct seabed features.

The Grand Banks Scour Catalogue was modified by deleting the first four crater features listed in Table 2.7. A corrected entry for Bowers Pit was added to the database, using feature dimensions based on the detailed surveys described by Barrie et al. (1986).

Further analysis of the Grand Banks Scour Catalogue showed the presence of 238 pairs of seabed features (pits and scours) with identical coordinates for the start point of the feature. These apparent duplicate features all originated from the Mobil database. Roughly 15% of the duplicate records were compared on a field-by-field basis. This comparison showed that, in general, the two records differed in only one or two field entries. The most common discrepancy was found in the old-id field, i.e. the entire record was identical except for the original identification code assigned to the feature. Some discrepancies were also found in the depth and end-point coordinate fields. Of the 238 apparent duplicate records, 236 were deleted from the database. In all cases the feature with the lowest value in the Scour ID field was retained.

The issue of duplicate entries in the database is particularly important for the deeper features, for which additional features may significantly affect any risk assessments based on pit depth. In order to address this concern, a subset of the pit database consisting of all pits with depths greater than or equal to 4.0 m was examined for potential duplicate entries. Starting with the deepest pit, a search was made for all other extreme-depth pits within a radius of approximately 2.0 km.

This review indicated that the set of extreme-depth pits (depths $\geq$ 4.0 m) were entirely associated with the Mobil catalogue, primarily the wellsite surveys (with the exception of the Texaco 89-01 pit, added during this project). Most of these pits were measured from wellsite surveys (77 out of 85) and thus appear in areal clusters limited by the boundaries of each individual wellsite survey. Thus, with the exception of the Bowers Pit area, all pits identified during each 2.0 km radius search described above were always associated with the same survey.

Duplicate entries for a single feature could occur within each individual survey, particularly when adjacent survey lines overlapped. However, the probability of duplicate records for the same feature occurring in the database would depend on the data analysis methods used and the quality control checks implemented during database development. Unfortunately, this information was not available for this project. Future work to further resolve this issue should be considered.

2.2.4 Feature Dimensions

An assessment of the level and quality of information on pit dimensions (depth, width and length) was also carried out as part of the review of the GBSC.

Depth Field

Two issues related to pit depth are of concern to any statistical analyses of the population of iceberg pits contained within the Grand Banks Scour Catalogue. The first issue concerns the methods used to measure pit depth, and the accuracy of those techniques for realistically representing the maximum depth of ice-scour features on the seabed. The second issue concerns the differentiation within the GBSC between shallow pits and those where depth was not actually measured.

All scour or pit depth values recorded in the GBSC represent measurements obtained from sub-bottom profiler systems, usually the Huntec Deep Tow System on regional survey lines and often the ORE 3.5 kHz or NSRF V-Fin system on wellsite surveys. Sub-bottom profiler systems survey a relatively narrow seabed swath, typically on the order of 10 to 20 m wide. The depths recorded in the GBSC represent the maximum depth observed on this narrow transect of the scour or pit, which may or may not have crossed the deepest part of the feature.

The potential error associated with estimation of the maximum pit depth based on a narrow survey swath is clearly illustrated by the two distinctly different depth values recorded for the duplicate entries for Bowers Pit from cruise 88-108 (7.0 m vs. 1.2 m; see Table 2.7). In fact, direct submersible measurements have shown the pit floor to be 10.0 m below the surrounding sea floor at the deepest point (Barrie et al. 1986).

Estimates of the direct error associated with the ability of the Huntec DTS to accurately measure the depth of a seabed feature range from 0.25 m (Geonautics Ltd. 1990), to more than 1.0 m, depending on instrument characteristics such as heave compensation and weather conditions at the time of survey (P. Simpkin, personal communication). The Bowers Pit example described above illustrates the potential for errors associated with the position of the survey track line relative to the deepest part of the pit to far exceed those errors associated with instrument resolution.

As described previously, the ways in which seabed ice-contact features were identified and measured varies between different portions of the GBSC database. For both components of the original Mobil study (regional lines and wellsite surveys), iceberg pits were included in the database only when seen on sub-bottom profiler records. Since each of these features was visible on the bottom profile, each iceberg pit in this portion of the database has a positive depth value. Some pits were discernible on the profiler data but were too small to measure; these have been included in the database with a depth of 0.5 m (instrument resolution) and a value of 3 in the depth_q field).

For the pipeline and wellsite surveys analysed during the Mobil update study, the data conversion process has resulted in no clear distinction between pits with depths less than the instrument resolution and those where depth was not measured. Both of these types of features have a value of 0.0 entered in the depth field; likely due to filling of blank fields with zeros during the data conversion process. Similar confusion exists in the remaining portions of the database, where a depth value of 0.0 was entered both for pits where depth was not measured and for those pits with depths less than the resolution of the sub-bottom profiler system.

Based on a review of the various fields in the GBSC database and the data conversion processes, the criteria given in Table 2.8 have been developed to differentiate between pits with small depths and those where depths were not measured.

Width Field

In the original Mobil survey, widths were recorded for iceberg pits for only the wellsite survey portion of the database. These width values are apparent widths, representing the pit width along the transect line where the survey track crossed the iceberg pit. If the pit was crossed at an oblique angle, the apparent width would be greater than the true width of the pit at this location. However, if the pit was not crossed at its widest point, the apparent width may be less than the true width of the widest part of the pit.

For the remainder of the data sources included in the GBSC., it is assumed that pit widths were measured from side scan sonar records and thus are a more realistic representation of actual pit width. However, for the portions of the database where pit widths and lengths were available, width values were often found to exceed length values (e.g., see Table 2.7, Scour ID 799). It is also not known whether slant-range and aspect-ratio corrections were carried out for all of the data sources.

Length Field

Length values have not been included in the GBSC for those iceberg pits originating from the Mobil databases. For the remaining data sources, the length value should only be considered accurate when the length_q field has a value of 2 or 5, indicating that the entire feature was visible on the side scan sonar record.

In the calculation of the width:length ratios described in Section 2.2.2 of this report, it became apparent that the length measurements for some of the features may be in error. Many features have UTM coordinates entered in the database for both the start and end points of the individual scour, crater, or scour segment (see Table 2.5). When the straight-line distance between the start and end points was calculated, this length was significantly greater than the value entered in the scour length field for many features. Without latitude and longitude values in degrees and minutes for each feature, it was not possible to determine whether the length field or the UTM coordinates were incorrect. Length data included in the Grand Banks Scour Catalogue should be used with caution.

2.3 Navigation Database

The Grand Banks Scour Catalogue contains information on each seabed ice-contact feature identified from the various data sources described above. However, the GBSC does not contain information on the actual area of the seabed covered by each individual survey. This information is required in order to differentiate between areas of the seabed that have been surveyed but no ice-contact features found, and areas of the seabed that have yet to be surveyed and analysed for ice-contact features.

In association with the development of the Grand Banks Scour Catalogue, a separate navigation database containing the associated survey data was developed (Canadian Seabed Research Ltd. 1992). The format of the navigation database as used for regional survey lines is given in Table 2.10.

For regional survey lines, the navigation database was based on the ship's navigation records. Each navigation fix position was entered in the database as a separate record. The navigation records indicate the total area of the seabed covered during each individual cruise. However, not all portions of the ship's track line had useful geophysical data or were analysed for ice-contact features. The USED field in the navigation database defines those portions of the ship's track where geophysical data were collected and analysed for seabed ice-contact features. Three values were employed in the USED field: a value of 1 indicates those portions of the survey line analysed for ice-contact features, a value of 2 indicates line segments not analysed for ice-contact features, and a value of 0 indicates that the extent of data availability and analysis was not known.

In general, wellsite surveys represent defined areas within the boundaries of which 100% of the seabed was surveyed and the geophysical data analysed for ice-contact features. Typically, a series of overlapping parallel survey lines with several perpendicular tie lines are used in wellsite surveys (see Terraquest Associates 1994). Rather than including the navigation data for each individual survey line, wellsite survey areas have been included in the navigation database as polygons defining the boundaries of each survey area.

2.3.1 Review and Completion of the Navigation Database

The navigation database was designed and partially completed under funding from the Geological Survey of Canada (Canadian Seabed Research Ltd. 1992). As part of the GSC project, the navigation database was completed for:

- the eight post-1983 AGC cruises (see Table 2.1);
- the ESRF Repetitive Mapping Ice Scour Catalogue (AGC cruise 90-021);
- AGC cruise 89-006;
- AGC cruises 80-010, 81-012, 82-039 and 83-033 (Mobil Ice Scour Catalogue, see Table 2.1).

At the completion of the GSC project, navigation data were missing for the remainder of the data sources included in the Mobil Ice Scour Catalogue and the post-1983 wellsite surveys.

Under funding from the ESRF project described in this report, additional work was completed on the navigation database by Canadian Seabed Research Ltd. (1994). This portion of the ESRF project was to include completion of the navigation database for the remaining data sources. At the completion of this task, the navigation database files were delivered to Sea Science together with the original version of the Grand Banks Scour Catalogue.

Subsequent review of the navigation database was undertaken by Sea Science. This review was based, where possible, on a comparison of the track lines plotted from the navigation database files supplied by Canadian Seabed Research Ltd. with hard copy plots from other sources. Information contained in the USED field was also examined for accuracy and completeness. The results of this review are discussed in the following material.

Post-1983 AGC Cruises

The post-1983 AGC cruises used in this study are listed in Table 2.1, with track lines plotted in Figure 2.3. For all eight post-1983 cruises, the USED field in the navigation database file (NAVBASE.DBF) was complete, with all records having values of 1 (line segment analysed for ice-contact features) or 2 (line segment not analysed). For the post-83 AGC cruises, both geophysical data analyses and the associated database development were completed by Canadian Seabed Research Ltd. under separate contract to the Geological Survey of Canada (Canadian Seabed Research Ltd. 1992). For the purposes of the current ESRF project, it has been assumed that the accuracy of this portion of the navigation database was reviewed through the previous GSC project. No further reviews were conducted under the ESRF study described in this report.

GBS Site Mosaic

The proposed site for the Hibernia Gravity Base Structure (GBS) was surveyed as part of AGC cruise 87-014, one of the post-1983 AGC cruises described above. It has been assumed that the accuracy of this portion of the navigation database has been previously reviewed.

ESRF Repetitive Mapping Ice Scour Catalogue

The ESRF Repetitive Mapping Ice Scour Catalogue (Geonautics Ltd. 1990, 1991) was developed from survey data obtained during AGC cruise 90-021, one of the eight post-1983 AGC cruises previously described. Navigation data for this cruise were compiled under funding from the Geological Survey of Canada (Canadian Seabed Research Ltd. 1992). Again, it has been assumed that the accuracy of this portion of the navigation database has been previously reviewed, and that this portion of cruise 90-021 has been correctly marked as analysed (value of 1 in USED field) in the NAVBASE.DBF file.

AGC Cruise 89-006 Database

The navigation data for AGC cruise 89-006 were compiled into NAVBASE format during the previous GSC project (Canadian Seabed Research Ltd. 1992). The accuracy of the track line plots for this portion of the navigation database has not been assessed by Sea Science. It should be noted that a database report was not available for the original ice scour database developed from this survey.

However, a review of the database file (NAVBASE.DBF) showed that the USED field is incomplete for this cruise. The entire cruise has a value of 0 entered in the USED field, indicating that the portions of the survey lines actually analysed for seabed ice-contact features is unknown. For the purposes of this project, it has been assumed that 100% of the track line represented in the NAVBASE.DBF file was analysed for ice-contact features.

Post-1983 Wellsite Surveys

Navigation data for the four post-1983 wellsite surveys were compiled by Canadian Seabed Research Ltd. (1994) under funding from the ESRF study described in this report. As described previously, wellsite survey areas have been included in the navigation database as polygons representing the boundaries of each wellsite survey area. The wellsite survey boundaries for the post-1983 wellsite surveys were plotted from the coordinates supplied by Canadian Seabed Research Ltd. (1994) and compared visually with a map of geophysical data coverage on northeastern Grand Bank (Geonautics Ltd. 1989). This comparison showed no apparent errors in this portion of the navigation database.

Mobil Ice Scour Catalogue - Regional Surveys

As previously described, data sources analysed for the Mobil Ice Scour Catalogue consist of regional surveys, pipeline route surveys and wellsite surveys. The regional surveys incorporated in the development of the original Mobil Ice Scour Catalogue (NORDCO Ltd. 1982) include the Hudson 80-010 cruise and the AGC/C-CORE Polaris V Cruise II (8000 series survey lines). The 1984 update to the Mobil catalogue added data from cruises 81-012, 82-039 and 83-033, and from three pipeline route surveys (Table 2.1).

Navigation data for cruises 80-010, 81-012, 82-039 and 83-033 were compiled into NAVBASE format during the previous GSC project (Canadian Seabed Research Ltd. 1992). As part of the current database review, navigation data for cruise 80-010 were plotted and compared with the large format, hard copy plot enclosed with the original database report (NORDCO Ltd. 1982). This comparison indicated that portions of the track lines were missing for this cruise. The USED field was also set at 0, or unknown, for the entire survey track.

Review of the geophysical data analysis procedures for cruise 80-010 (Tables 2.1 and 2.3) indicated that iceberg pits were identified from Huntec data only, and that only the portions of the survey lines within the Mobil study area were analysed. Consequently, a new navigation database representing the Huntec coverage for cruise 80-010 was created by Gary Sonnichsen of AGC. The navigation lines created from this new database were subsequently clipped to include only those line segments inside the Mobil study area (see Figure 2.2); it was then assumed that 100% of the Huntec data inside the Mobil study area were analysed for iceberg pits.

Plots of the navigation data for regional cruises 82-039 and 83-033 were compared with a map of regional geophysical data coverage for the Grand Banks (Geonautics Ltd. 1985). No independent track plot was available for cruise 81-012. Although the navigation database for cruises 82-039 and 83-033 appeared to agree well with the Geonautics map, it was not clear from the Mobil database report (NORDCO Ltd. 1984) which portions of these surveys had actually been analysed for iceberg pits. Again, the USED field was set at unknown for all three surveys. It should be noted that the majority of the cruise 82-039 survey lines are outside of the Mobil study area.

A review of the geophysical data analysis methods used for these three surveys also indicated some uncertainty as to the methods used to identify iceberg pits. Since only 8 iceberg pits are associated with these three cruises, it was decided to omit these surveys in the data analyses described in the remainder of this report.

Navigation data for the 8000 series lines (ACG/C-CORE Polaris V Cruise II) were compiled by Canadian Seabed Research Ltd. (1994) under funding from the ESRF project described in this report. The track lines from this portion of the navigation database were plotted and compared with Figure 8 and Table 3 of the original Mobil database report (NORDCO Ltd. 1982). This comparison indicated that the northern pipeline route and the three mosaic areas were missing from the navigation database.

A new navigation database for the 8000 series lines, including the northern pipeline route, was created by Gary Sonnichsen of AGC. Navigation shotpoints were digitized from plastic copies of track plots provided to C-CORE by McElhanney Surveying & Engineering Ltd. (G. Sonnichsen, pers. comm.), and from the Geonautics Ltd. (1985) map of regional data coverage over the Grand Banks of Newfoundland.

The USED field was set as unknown for the entire survey. Although sufficient information is available in the NORDCO Ltd. (1982) report to determine which portions of the 8000 series lines were analysed for ice-contact features, the level of effort to do so was beyond the scope of this project. It has been assumed that 100% of the survey lines were analysed for iceberg pits, with the exception of the westward extension of the northern pipeline route. This survey line was clipped at the boundary of the Mobil study area (Figure 2.2).

Navigation data for the pipeline surveys included in the 1984 update to the Mobil Ice Scour Catalogue were digitized by Canadian Seabed Research Ltd. (1994) under funding from the current ESRF project. However, a review of these navigation data indicated that navigation lines had been supplied only for cruise code 26 (Geonautics d'Appolonia 1982 survey for Mobil Oil). Review of the ice-contact features contained in the Grand Banks Scour Catalogue showed that a significant number of iceberg pits were associated with cruise codes 23, 24 and 25; these cruise codes were previously unidentified and lacked navigation data.

These cruises were identified with the assistance of Gary Sonnichsen of the Atlantic Geoscience Centre, who digitized track lines for the appropriate surveys (Table 2.1) and supplied navigation data in database format. Navigation data were plotted and visually checked against hard copy maps of the corresponding surveys. For all three pipeline surveys (cruise codes 23, 24, 25 and 26), it has been assumed that 100% of the survey lines were analysed for iceberg pits.

Mobil Ice Scour Catalogue - Wellsite Surveys

Navigation data for the 21 wellsite surveys included in the Mobil Ice Scour Catalogue were compiled by Terraquest Associates (1994) under separate contract to the Geological Survey of Canada. Boundary coordinates for each wellsite were supplied to Canadian Seabed Research Ltd., who converted the boundary coordinates for each wellsite to polygons in GIS format. These polygons were then compared visually with the wellsite survey boundaries shown on the Geonautics Ltd. (1989) map of data coverage on northeastern Grand Bank. This comparison showed no apparent errors in this portion of the navigation database.

Table 2.1
Regional Survey Summary Table
Grand Banks Scour Catalogue

Cruise Code	Survey	References	Instrumentation	Survey Region	No. of Pits (Original GBSC, Revised GBSC)
Mobil Ice Scour Catalogue Original Study		**NORDCO (1982)**			
80010	Hudson 80-010	G. Sonnichsen (pers. comm.)	• Huntec DTS profiler • BIO 70 kHz side scan	• Regional survey covering northeastern Grand Bank; two lines crossing the southern bank; one line west to Green Bank. • Two mosaics on northeastern Grand Bank • Only data within study area analysed for ice-contact features	20 20
8000	AGC/C-CORE Polaris V Cruise II	Simpkin (1981) G. Sonnichsen (pers. comm.)	• Huntec DTS profiler • ORE 100 kHz side scan	• Series of 20 parallel track lines at 4 km spacing on northeastern Grand Bank • Three detailed mosaic sites on northeastern Grand Bank • Northern Pipeline Route extending from northeastern Grand Bank to Newfoundland coast • Only data within study area analysed for ice-contact features	6 6
4000	4000 Series Lines	Geomarine Associates Ltd. (1980)	• ORE 100 kHz side scan	• Series of 10 parallel track lines at 2 km spacing on northeastern Grand Bank • Data analysed only for iceberg scours, pits not included	
Mobil Ice Scour Catalogue Update Study		**NORDCO (1984)**			
81012	Baffin 81-012		• Huntec DTS profiler (?) • BIO 70 kHz side scan	• Focus on northeastern Grand Bank • Data primarily within study area for Mobil Ice Scour Catalogue	8 6
82039	Baffin 82-039		• Huntec DTS profiler (?) • Klein 100 kHz side scan	• Four parallel survey lines over central Grand Bank, roughly 250 km in length and spaced 40 km apart • Data primarily outside of study area for Mobil Ice Scour Catalogue; unclear how much data analysed for ice-contact features	0 0
83033	Hudson 83-033		• Huntec DTS profiler (?) • Klein 100 kHz side scan	• Focus on northeastern Grand Bank • Data primarily within study area for Mobil Ice Scour Catalogue	2 2
23	Hibernia Pipeline Survey, Southern Route	Geonautics Ltd. (1984)	• Huntec DTS profiler • ORE 100 kHz side scan	• Regional survey extending from the south coast of Newfoundland to the Hibernia area • Several east- to northeast-trending survey lines • Data primarily outside of study area for Mobil Ice Scour Catalogue, but appears that all data were analysed for ice-contact features	352 178
24, 25	Hibernia Pipeline Survey, Southern Route	Simpkin (1981)	• Huntec DTS profiler • ORE 100 kHz side scan	• Single survey line with east-west segment extending west to Newfoundland coast, northerly segment crossing Avalon Channel • Data outside of study area for Mobil Ice Scour Catalogue but appears that all data were analysed for ice-contact features	27 27

Table 2.1
Regional Survey Summary Table
Grand Banks Scour Catalogue

Cruise Code	Survey	References	Instrumentation	Survey Region	No. of Pits (Original GBSC, Revised GBSC)
Mobil Ice Scour Catalogue Original Study		**NORDCO (1982)**			
80010	Hudson 80-010	G. Sonnichsen (pers. comm.)	• Huntec DTS profiler • BIO 70 kHz side scan	• Regional survey covering northeastern Grand Bank; two lines crossing the southern bank; one line west to Green Bank. • Two mosaics on northeastern Grand Bank • Only data within study area analysed for ice-contact features	20 20
8000	AGC/C-CORE Polaris V Cruise II	Simpkin (1981) G. Sonnichsen (pers. comm.)	• Huntec DTS profiler • ORE 100 kHz side scan	• Series of 20 parallel track lines at 4 km spacing on northeastern Grand Bank • Three detailed mosaic sites on northeastern Grand Bank • Northern Pipeline Route extending from northeastern Grand Bank to Newfoundland coast • Only data within study area analysed for ice-contact features	6 6
4000	4000 Series Lines	Geomarine Associates Ltd. (1980)	• ORE 100 kHz side scan	• Series of 10 parallel track lines at 2 km spacing on northeastern Grand Bank • Data analysed only for iceberg scours, pits not included	
Mobil Ice Scour Catalogue Update Study		**NORDCO (1984)**			
81012	Baffin 81-012		• Huntec DTS profiler (?) • BIO 70 kHz side scan	• Focus on northeastern Grand Bank • Data primarily within study area for Mobil Ice Scour Catalogue	8 6
82039	Baffin 82-039		• Huntec DTS profiler (?) • Klein 100 kHz side scan	• Four parallel survey lines over central Grand Bank, roughly 250 km in length and spaced 40 km apart • Data primarily outside of study area for Mobil Ice Scour Catalogue; unclear how much data analysed for ice-contact features	0 0
83033	Hudson 83-033		• Huntec DTS profiler (?) • Klein 100 kHz side scan	• Focus on northeastern Grand Bank • Data primarily within study area for Mobil Ice Scour Catalogue	2 2
23	Hibernia Pipeline Survey, Southern Route	Geonautics Ltd. (1984)	• Huntec DTS profiler • ORE 100 kHz side scan	• Regional survey extending from the south coast of Newfoundland to the Hibernia area • Several east- to northeast-trending survey lines • Data primarily outside of study area for Mobil Ice Scour Catalogue, but appears that all data were analysed for ice-contact features	352 178
24, 25	Hibernia Pipeline Survey, Southern Route	Simpkin (1981)	• Huntec DTS profiler • ORE 100 kHz side scan	• Single survey line with east-west segment extending west to Newfoundland coast, northerly segment crossing Avalon Channel • Data outside of study area for Mobil Ice Scour Catalogue but appears that all data were analysed for ice-contact features	27 27

26	Geonautics D'Appolonia 1982 Survey for Mobil Oil	no reference available	• unknown profiler and side scan systems; assumed Huntec DTS and ORE 100 kHz	• Data covers region between Avalon Peninsula and Green and Whale Banks • Grid pattern with 10 north-south lines spaced roughly 15 km apart; three main east-west lines • Data outside of study area for Mobil Ice Scour Catalogue but appears that all data were analysed for ice-contact features	75 75
ESRF Repetitive Mapping Ice Scour Catalogue		**Geonautics (1990, 1991)**			
90021			• Huntec DTS profiler • Klein 50 kHz and ORE 100 kHz side scans	• ESRF repetitive mapping survey of the 4000 Series lines on northeastern Grand Bank	16 15
AGC Cruise 89-006 Database		**no report available**			
89006		G. Sonnichsen (pers. comm.)	• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Regional survey covering northern Downing Basin • Five main north-south lines; three main east-west lines	77 72
Post-1983 AGC Cruises		**Canadian Seabed Research Ltd. (1992)**			
84024	84-024		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Avalon Channel, northwestern Grand Bank	65 51
85005	85-005		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Hibernia region, eastern Grand Bank south of 46°30'N, southern Grand Bank, Avalon Channel and the northern portion of Whale Bank	10 8
85057	85-057		• 3.5 kHz sub-bottom profiler • Klein 100 kHz side scan	• One line of regional data along the eastern margin of Grand Bank • Additional data from Bowers Pit and Ocean Ranger areas and Avalon Channel not examined	2 2
86017	86-017		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Green Bank, Whale Bank, Halibut Channel, Haddock Channel, Avalon Channel and the western portion of Grand Bank • Halibut Channel data not examined	50 44
86018	86-018		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Northeastern Grand Bank • Regional lines and detailed survey areas	59 37
87014	87-014		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• One line of regional data between Hibernia area and Carson Canyon • Detailed surveys at sites within Downing Basin, over a buried channel system on northern Grand Bank, at the Hibernia GBS site, and at selected sites near Carson Canyon and on southern Grand Bank	0 0
88108	88-108		• Huntec DTS profiler • BIO 70 kHz and Klein 100 kHz side scans	• Northeastern Grand Bank and Flemish Pass	106 72
90021	90-021		• Huntec DTS profiler • Klein 50 kHz and ORE 100 kHz side scans	• Regional survey of northeastern Grand Bank • Site-specific surveys of Scour 95, Scour 89-01 and the Terra Nova glory hole • ESRF repetitive mapping survey of the 4000 Series lines	66 25

Table 2.2
Wellsite Survey Summary Table
Grand Banks Scour Catalogue

Cruise Code	Survey	References	Instrumentation	Water Depth (m) (min - max)	No. of Pits (Original GBSC, Revised GBSC)
Mobil Ice Scour Catalogue Original Study		**NORDCO Ltd. (1982)**			
10	White Rose Flank	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	110 - 127	0 0
11	Ben Nevis	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	96 - 102	0 0
12	Hibernia P-15	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	78 - 84	1 1
13	Cumberland	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	189 - 235	82 82
14	Dana North and South	Terraquest Associates (1994)	• Huntec DTS and ORE 3.5 kHz profilers • ORE 100 kHz side scan	202 - 205 (North) 239 - 260 (South)	158 158
15	Hebron	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	83 -99	0 0
16	Hibernia North	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	78 - 86	0 0
17	Nautilus	Terraquest Associates (1994)	• Huntec DTS and ORE 3.5 kHz profilers • ORE 100 kHz side scan	81 - 98	0 0
18	Ragnar	Terraquest Associates (1994)	• Huntec DTS and ORE 3.5 kHz profilers • ORE 100 kHz side scan	184 - 222	56 56
19	Rankin	Terraquest Associates (1994)	• Huntec DTS and ORE 3.5 kHz profilers • ORE 100 kHz side scan	70 - 82	0 0
20	Tempest North	Terraquest Associates (1994)	• echo sounder • ORE 100 kHz side scan	146 - 162	0 0
21	Trave/White Rose	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	115 - 149	0 0

22	West Hibernia	Terraquest Associates (1994)	• ORE 3.5 kHz profiler • ORE 100 kHz side scan	75 - 84	0 0
Mobil Ice Scour Catalogue Update Study		**NORDCO Ltd. (1984)**			
1	Archer Flank	Terraquest Associates (1994)	• NSRF V-Fin profiler • ORE 100 kHz and Klein 100 kHz side scans	114 - 132	94 93
2	Bonanza	Terraquest Associates (1994)	• NSRF V-Fin profiler • ORE 100 kHz side scan	181 - 211	140 139
3	Dominion	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	156 - 166	129 129
5	Linnet	Terraquest Associates (1994)	• NSRF V-Fin profiler • ORE 100 kHz and Klein 100 kHz side scans	119 - 204	43 43
6	Mara	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	80 - 100	10 9
7	Saronac	Terraquest Associates (1994)	• NSRF V-Fin profiler • ORE 100 kHz side scan	168 - 204	257 252
8	Titus	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	160 - 206	153 153
9	Voyager	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	92 - 103	0 0
Post-1983 Wellsites		**Canadian Seabed Research Ltd. (1992)**			
27	Burin Bonne Bay	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	100 - 109	0 0
28	North Ben Nevis (Husky)	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	101 - 104	0 0
29	North Ben Nevis Rev-1	Terraquest Associates (1994)	• Huntec DTS profiler • ORE 100 kHz side scan	100 - 102	4 4
30	South Brook	Terraquest Associates (1994)	• NSRF V-Fin profiler • Klein 100 kHz side scan	85 - 92	3 3

Table 2.3
Iceberg Scour and Pit Identification
Grand Banks Scour Catalogue

Data Source	Cruise Codes	Pits	Scours
Mobil original study regional lines	8000 80010	-pits recorded only when seen on Huntec data; side scan data used to confirm nature of feature -all observed pits included in database (?)	-scours recorded only when seen on Huntec data; side scan data used to confirm nature of feature -only "fresh-looking" scours included in database
Mobil original study wellsite surveys	10-22	-pits recorded only when seen on sub-bottom profiler data; side scan used to confirm nature of feature -all observed pits included in database (?)	-scours recorded when seen on either sub-bottom profiler or side scan data -only "fresh-looking" scours included in database
Mobil original study 4000 series lines	4000	-data not analysed for pits	-scours recorded when seen on side scan data -only "fresh-looking" scours included in database (?)
Mobil update study regional lines	81012 82039 83033	-pits recorded when seen on either sub-bottom profiler or side scan data (?) -all observed pits included in database (?)	-scours recorded when seen on sub-bottom profiler or side scan data -only "fresh-looking" scours included in database
Mobil update study pipeline surveys	23 24 25 26	-pits recorded when seen on sub-bottom profiler or side scan data -all observed pits included in database (?)	-scours recorded when seen on sub-bottom profiler or side scan data -only "fresh-looking" scours included in database
Mobil update study wellsite surveys	1-3 5-9	-pits recorded when seen on sub-bottom profiler or side scan data -all observed pits included in database (?)	-scours recorded when seen on sub-bottom profiler or side scan data -only "fresh-looking" scours included in database

AGC Cruise 89-006 Database	89006	-no database report available -pits recorded when seen on side scan data (?) -all pits in water depths less than 110 m included in database -only recent-looking pits in water depths greater than 110 m included in database (?)	-no database report available -scours recorded when seen on side scan data (?) -all scours in water depths less than 110 m included in database -only recent-looking scours in water depths greater than 110 m included in database
ESRF 4000 Series Database	90021, Source 4	-pits recorded when seen on side scan data only -all pits included in database	-scours recorded when seen on side scan data only -all scours included in database
GBS Mosaic Site	87014, Source 2	-no observed pits	-six scours taken from surficial geology map -all scours included in database (water depth less than 110 m)
Post-1983 Wellsites	27 28 29 30	-information obtained from wellsite survey reports -pits recorded when seen on side scan data only -only wellsites in water depths less than 110 m considered	-information obtained from wellsite survey reports -scours recorded when seen on side scan data only -only wellsites in water depths less than 110 m considered
Post-1983 AGC Cruises	84024 85005 85057 86017 86018 87014 88108 90021	-pits recorded when seen on side scan data only -all pits in water depths less than 110 m included in database -only "fresh-appearing" pits in water depths greater than 110 m included in database	-scours recorded when seen on side scan data only -all scours in water depths less than 110 m included in database -only "fresh-appearing" scours in water depths greater than 110 m included in database

Table 2.4
Distribution of Observed Craters and Scours By Data Source
Grand Banks Scour Catalogue

Data Source	PITS			SCOURS		
	Regional Surveys	Wellsite Surveys	TOTAL	Regional Surveys	Wellsite Surveys	TOTAL
Mobil Ice Scour Catalogue						
Original Study	26	297	323	560*	358	918
Update Study	464	826	1290	194	431	625
ESRF 4000 Series Repetitive Mapping Surveys	16		16	264		264
AGC Cruise 89-006 Database	77		77	111		111
Post-1983 AGC Cruises	358		358	952		952
Post-1983 Wellsite Surveys		7	7		40	40
GBS Site Mosaic		0	0	6		6
TOTALS	941	1130	2071	2087	829	2916

*Includes the 82 scours from the original survey of the 4000 Series lines

Table 2.5
Database Structure
Grand Banks Scour Catalogue

Field	Field Name	Type	Width	Dec	Description
1	SCOUR_ID	NUM	6		UNIQUE SCOUR IDENTIFIER
2	SOURCE	NUM	2		DATA SOURCE (TABLE)
3	CRUISE	NUM	6		CRUISE # & CODES (TABLE)
4	DAY	NUM	4		JULIAN DAY
5	S_STIME	NUM	6	1	SCOUR SEGMENT START TIME
6	BATHY	NUM	4		BATHYMETRY - METRES
7	TYPE	CHAR	1		SCOUR OR CRATER IDENTIFIER (TABLE)
8	PLN_S	NUM	3		PLAN SHAPE (TABLE)
9	SEG	NUM	3		UNIQUE SEGMENT IDENTIFIER
10	SBP	NUM	3		SUB-BOTTOM PROFILER (TABLE)
11	DEPTH	NUM	4	1	SCOUR DEPTH - METRES
12	DEPTH_Q	NUM	2		DEPTH QUALIFIER (TABLE)
13	WIDTH	NUM	5		SCOUR SEGMENT WIDTH - METRES
14	LENGTH	NUM	6		SCOUR SEG. LENGTH - METRES
15	LENGTH_Q	NUM	2		SCOUR END POINT QUAL. (TABLE)
16	ORIENT	NUM	4		SCOUR SEGMENT ORIENTATION
17	NORTHING_S	NUM	8		SEG/SCOUR START UTM COORDINATES
18	EASTING_S	NUM	7		"
19	NORTHING-E	NUM	8		SEG/SCOUR END UTM COORDINATES
20	EASTING_E	NUM	7		"
21	BERM_HT1	NUM	3	1	BERM HEIGHT - METRES
22	BERM-HT2	NUM	3	1	2ND BERM HEIGHT - METRES
23	PROFL	CHAR	1		PROFILE TYPE (TABLE)
24	B_70	NUM	4		B.I.O. 70 kHz
25	K_100	NUM	4		KLEIN 100 kHz
26	O_100	NUM	4		O.R.E. 100 kHz
27	K_50	NUM	4		KLEIN 50 kHz
28	C_AVL	CHAR	1		CHANNEL AVAILABLE
29	RANGE-CHNL	NUM	4		RANGE PER CHANNEL - METRES
30	EFF_RANGE	NUM	4		EFFECTIVE RANGE - METRES
31	QUAL	NUM	2		RECORD QUALITY (TABLE)
32	CLAR	NUM	2		SCOUR CLARITY (TABLE)
33	B_DEV	NUM	2		BERM DEVELOPMENT (TABLE)
34	SED	NUM	2		SEDIMENT TYPE (TABLE)
35	REG_SED	NUM	2		REGIONAL SEDIMENT TYPE (TABLE)
36	HEAD	NUM	4		SHIPS HEADING 0 - 359
37	NAV_AVAIL	NUM	2		NAVIGATION AVAILABILITY (TABLE)
38	ANLST	NUM	2		ANALYST (TABLE)
39	D_ANLSIS	DATE	8		DATE OF ANALYSIS
40	OLD_ID	CHAR	7		SOURCE FILES UNIQUE SCOUR ID
41	COMM	MEMO	10		COMMENT FIELD

Revision Date:	October 14, 1992
Structure for Database:	GBSC.DBF
Number of data records:	5777

Table 2.6
Scours With Craters - Feature Type Revisions
Revised Grand Banks Scour Catalogue

Scour ID	Segment	Old Type	Comment Type	W:L Ratio	Visible Endpoints	Ratio Type	Change?	New Type
2	1	C	?	0.06	2	S	Y	S
	2	C	?	0.09	2	S	Y	S
	3	C	?	0.14	2	S	Y	S
	4	C	?	0.30	2	S	Y	S
	5	C	?	0.78	2	C	N	C
44	1	C	?	0.12	2	S	Y	S
	2	C	?	0.57	2	C	N	C
46	1	C	?	0.50	2	C	Y	S
	2	C	?	0.76	2	C	N	C
53	1	C	?	0.73	2	C	Y	S
	2	C	?	0.96	2	C	N	C
	3	C	?	0.43	2	C	Y	S
82	1	C	?	0.77	1	C	N	C
	2	C	?	0.38	1	C	Y	S
	3	C	?	0.23	1	S	Y	S
86	1	C	?	0.57	1	C	N	C
	2	C	?	0.09	1	S	Y	S
	3	C	?	0.20	1	S	Y	S
	4	C	?	0.23	1	S	Y	S
92	1	C	?	0.43	2	C	Y	S
	2	C	?	1.34	2	C	N	C
138	1	C	?	0.07	2	S	Y	S
	2	C	?	0.62	2	C	N	C
232	1	C	?	0.33	2	S	Y	S
	2	C	?	0.25	2	S	Y	S
	3	C	?	0.50	2	C	N	C
263	1	C	?	1.52	2	C	N	C
	2	C	?	0.37	2	C	Y	S
314	1	C	S	0.11	2	S	Y	S
	2	C	S	0.10	2	S	Y	S
	3	C	C	0.55	2	C	N	C
	4	C	C	0.68	2	C	N	C
319	1	C	S	0.19	1	S	Y	S
	2	C	S	0.38	1	S	Y	S
	3	C	C	1.49	1	C	N	C
	4	C	S	0.10	1	S	Y	S
321	1	C	?	0.18	1	S	Y	S
	2	C	?	1.14	1	C	N	C
343	1	C	?	0.41	1	C	N	C
	2	C	?	0.18	1	S	Y	S
	3	C	?	0.13	1	S	Y	S
	4	C	?	0.09	1	S	Y	S

374	1	C	?	0.24	1	S	Y	S
	2	C	?	0.62	1	C	Y	S
	3	C	?	0.66	1	C	N	C
437	1	C	?	0.03	1	S	Y	S
	2	C	?	0.07	1	S	Y	S
	3	C	?	0.53	1	C	Y	S
	4	C	?	1.34	1	C	N	C
448	1	C	?	0.06	1	S	Y	S
	2	C	?	0.01	1	S	Y	S
	3	C	?	1.66	1	C	N	C
455	1	C	?	2.00	1	C	N	C
	2	C	?	0.23	1	S	Y	S
	3	C	?	0.01	1	S	Y	S
	4	C	?	0.07	1	S	Y	S
	5	C	?	0.23	1	S	Y	S
519	1	C	S	0.31	1	S	Y	S
	2	C	S	0.06	1	S	Y	S
	3	C	C	0.64	1	C	N	C
530	1	C	S	0.05	1	S	Y	S
	2	C	C	0.34	1	C	N	C
565	1	C	?	0.03	1	S	Y	S
	2	C	?	0.14	1	S	Y	S
	3	C	?	1.24	1	C	N	C
620	1	C	?	0.55	1	C	N	C
	2	C	?	0.15	1	S	Y	S
	3	C	?	0.24	1	S	Y	S
	4	C	?	0.14	1	S	Y	S
667	1	C	?	1.18	1	C	N	C
	2	C	?	0.13	1	S	Y	S
	3	C	?	0.02	1	S	Y	S
670	1	C	S?	0.27	1	S	Y	S
683	1	C	?	0.24	2	S	Y	S
	2	C	?	0.08	2	S	Y	S
	3	C	?	0.22	2	S	Y	S
	4	C	?	0.40	2	C	N	C
696	1	C	S	0.32	2	S	Y	S
	2	C	C	0.83	2	C	N	C
713	1	C	?	0.36	1	C	N	C
	2	C	?	0.05	1	S	Y	S
	3	C	?	0.11	1	S	Y	S
715	1	C	S	0.27	2	S	Y	S
	2	C	S	0.03	2	S	Y	S
	3	C	C	1.15	2	C	N	C
	4	C	S	0.07	2	S	Y	S
723	1	C	?	0.04	1	S	Y	S
	2	C	?	0.49	1	C	N	C
730	1	C	?	0.88	2	C	Y	S
	2	C	?	1.07	2	C	N	C
	3	C	?	0.07	2	S	Y	S

739	1	C	?	0.13	1	S	Y	S
	2	C	?	0.46	1	C	N	C
744	1	C	?	0.18	2	S	Y	S
	2	C	?	0.37	2	C	N	C
	3	C	?	0.27	2	S	Y	S
763	1	C	?	1.10	1	C	N	C
	2	C	?	0.04	1	S	Y	S
803	1	C	?	0.97	1	C	N	C
	2	C	?	0.04	1	S	Y	S
850	1	C	?	0.06	NO	S	Y	S
	2	C	?	0.02	NO	S	Y	S
	3	C	?	0.04	NO	S	Y	S
	4	C	?	0.02	NO	S	Y	S
	5	C	?	0.72	NO	C	N	C
915	1	C	C	0.62	1	C	N	C
	2	C	S	0.12	1	S	Y	S
	3	C	S	0.10	1	S	Y	S
	4	C	C	0.64	1	C	N	C
	5	C	S	0.04	1	S	Y	S
917	1	C	C	0.82	1	C	N	C
	2	C	S	0.32	1	S	Y	S
	3	C	S	0.11	1	S	Y	S
924	1	C	C	0.88	1	C	N	C
	2	C	S	0.17	1	S	Y	S
	3	C	S	0.14	1	S	Y	S
	4	C	S	0.06	1	S	Y	S
936	1	C	?	1.27	1	C	N	C
	2	C	?	0.30	1	S	Y	S
	3	C	?	0.14	1	S	Y	S
963	1	C	?	0.12	1	S	Y	S
	2	C	?	0.56	1	C	N	C
965	1	C	?	0.15	NO	S	Y	S
	2	C	?	0.58	NO	C	N	C
	3	C	?	0.19	NO	S	Y	S
973	1	C	?	0.31	2	S	Y	S
	2	C	?	0.47	2	C	Y	S
	3	C	?	0.28	2	S	Y	S
	4	C	?	0.80	2	C	N	C
974	1	C	?	0.31	1	S	Y	S
	2	C	?	1.04	1	C	N	C
975	1	C	?	0.86	2	C	N	C
	2	C	?	0.49	2	C	Y	S
	3	C	?	0.42	2	C	Y	S
	4	C	?	0.17	2	S	Y	S
991	1	C	?	0.79	1	C	N	C
	2	C	?	0.04	1	S	Y	S
996	1	C	?	0.90	2	C	N	C
	2	C	?	0.09	2	S	Y	S
	3	C	?	0.42	2	C	Y	S

1004	1	C	S	0.23	2	S	Y	S
	2	C	S	0.25	2	S	Y	S
	3	C	C	0.90	2	C	N	C
	4	C	S	0.61	2	C	Y	S
	5	C	S	0.23	2	S	Y	S
	6	C	S	0.11	2	S	Y	S
1051	1	C	S	0.06	1	S	Y	S
	2	C	C	0.80	1	C	N	C
	3	C	C	0.94	1	C	N	C
	4	C	S	0.10	1	S	Y	S
1078	1	C	C	0.83	1	C	N	C
	2	C	S	1.19	1	C	Y	S
	3	C	S	0.15	1	S	Y	S
	4	C	S	0.15	1	S	Y	S
	5	C	S	0.27	1	S	Y	S
	6	C	S	0.14	1	S	Y	S
	7	C	S	0.15	1	S	Y	S
	8	C	S	0.22	1	S	Y	S
	9	C	S	0.10	1	S	Y	S
	10	C	S	0.05	1	S	Y	S
1081	1	C	?	0.42	1	C	Y	S
	2	C	?	0.76	1	C	N	C

Notes:

1. Ratio type determined based on W:L ratios, where W:L in (0.33, 3.0) for craters
2. Scour ID 670 - Crater is not included in GBSC, noted in comment field as "beyond the end of line"

Table 2.7
Potential Duplicate Entries for Bowers Pit
Grand Banks Scour Catalogue

Scour ID	Cruise	Depth	Width	Length
565	88108	7.0	82	66*
799	88108	1.2	76	56
1081	90021	n/a	98	129*
3395	Mara	7.0	125	n/a
3396	Mara	n/a	35	n/a
3397	Mara	n/a	60	n/a

*only one end of the pit was clearly visible on the sidescan record; length measurement may not be accurate

Table 2.8
Criteria for Interpretation of Depth Measurements
Grand Banks Scour Catalogue

Depth Field	Depth_q Field	Actual Depth
0.0 or >0.0	1 or 3	instrument resolution or less
0.0	blank, 0, 2 or 5	depth not measured
>0.0	blank	depth recorded in database

Table 2.9
Distribution of Observed Craters and Scours By Data Source
Revised Grand Banks Scour Catalogue

Data Source	PITS			SCOURS		
	Regional Surveys	Wellsite Surveys	TOTAL	Regional Surveys	Wellsite Surveys	TOTAL
Mobil Ice Scour Catalogue						
Original Study	26	297	323	551*	349	900
Update Study	288	818	1106	157	426	583
ESRF 4000 Series Repetitive Mapping Surveys	15		15	265		265
AGC Cruise 89-006 Database	72**		72	111		111
Post-1983 AGC Cruises	239		239	951		951
Post-1983 Wellsite Surveys		7	7		40	40
GBS Site Mosaic		0	0	6		6
Bowers Pit	1		1			
TOTALS	641	1122	1763	2041	815	2856

*Includes the 82 scours from the original survey of the 4000 Series lines
**Includes Texaco 89-01 pit

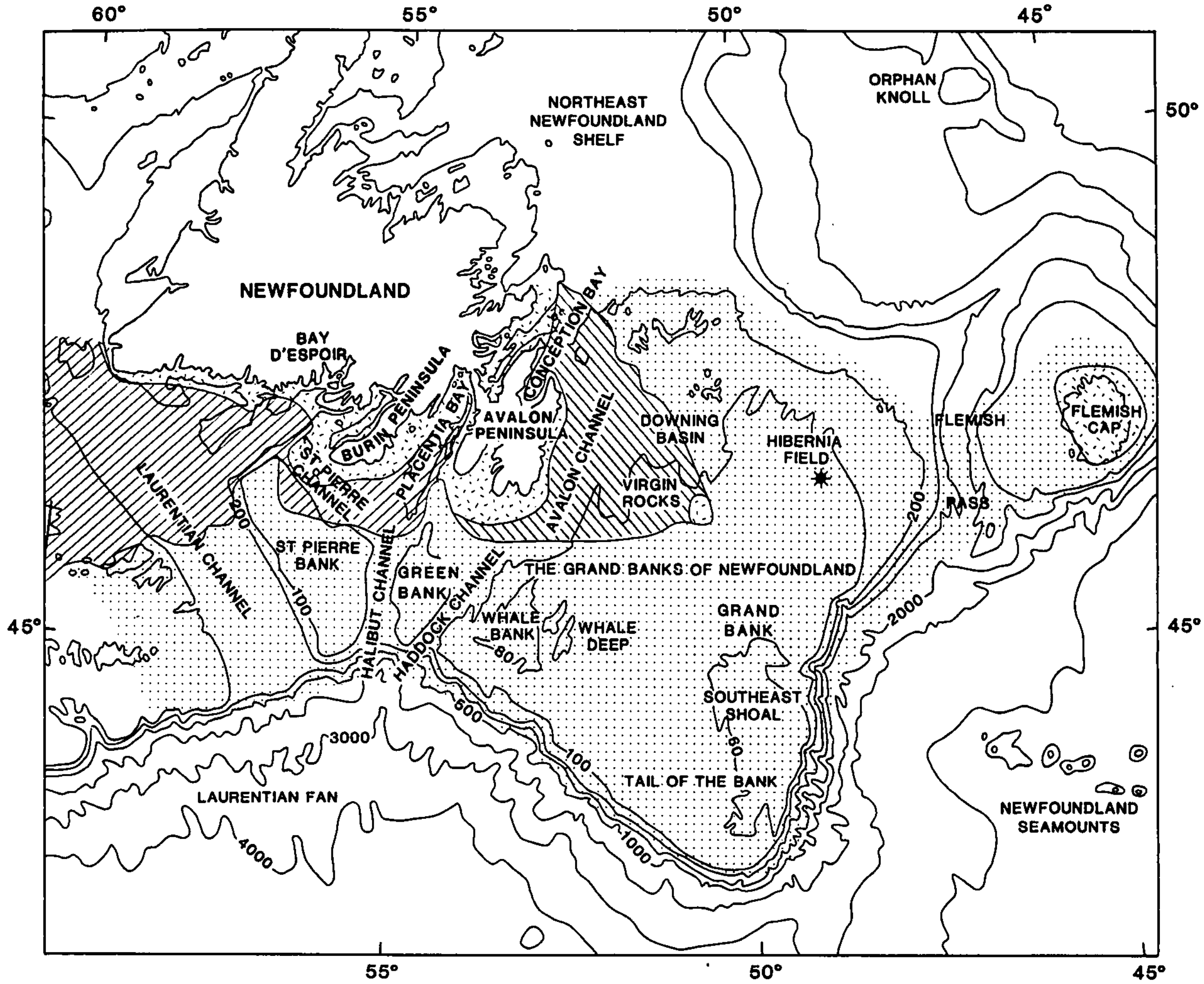


Figure 2.1 **Place names on the Grand Banks of Newfoundland (from Piper et al. 1990).**

Table 2.10
Field Format
Navigation Database

Field	Field Name	Type	Width	Dec	Description
1	CRUISE	NUM	5		CRUISE IDENTIFIER
2	LINE	NUM	8	2	LINE NUMBER
3	DAY	NUM	3		JULIAN DAY
4	HOUR	NUM	2		FIX TIME, HOUR
5	MIN	NUM	2		FIX TIME, MINUTE
6	LAT	NUM	8	5	LATITUDE
7	LONG	NUM	9	5	LONGITUDE
8	NORTH	NUM	10	1	UTM NORTHING
9	EAST	NUM	10	1	UTM EASTING
10	USED	NUM	2		NAV USED

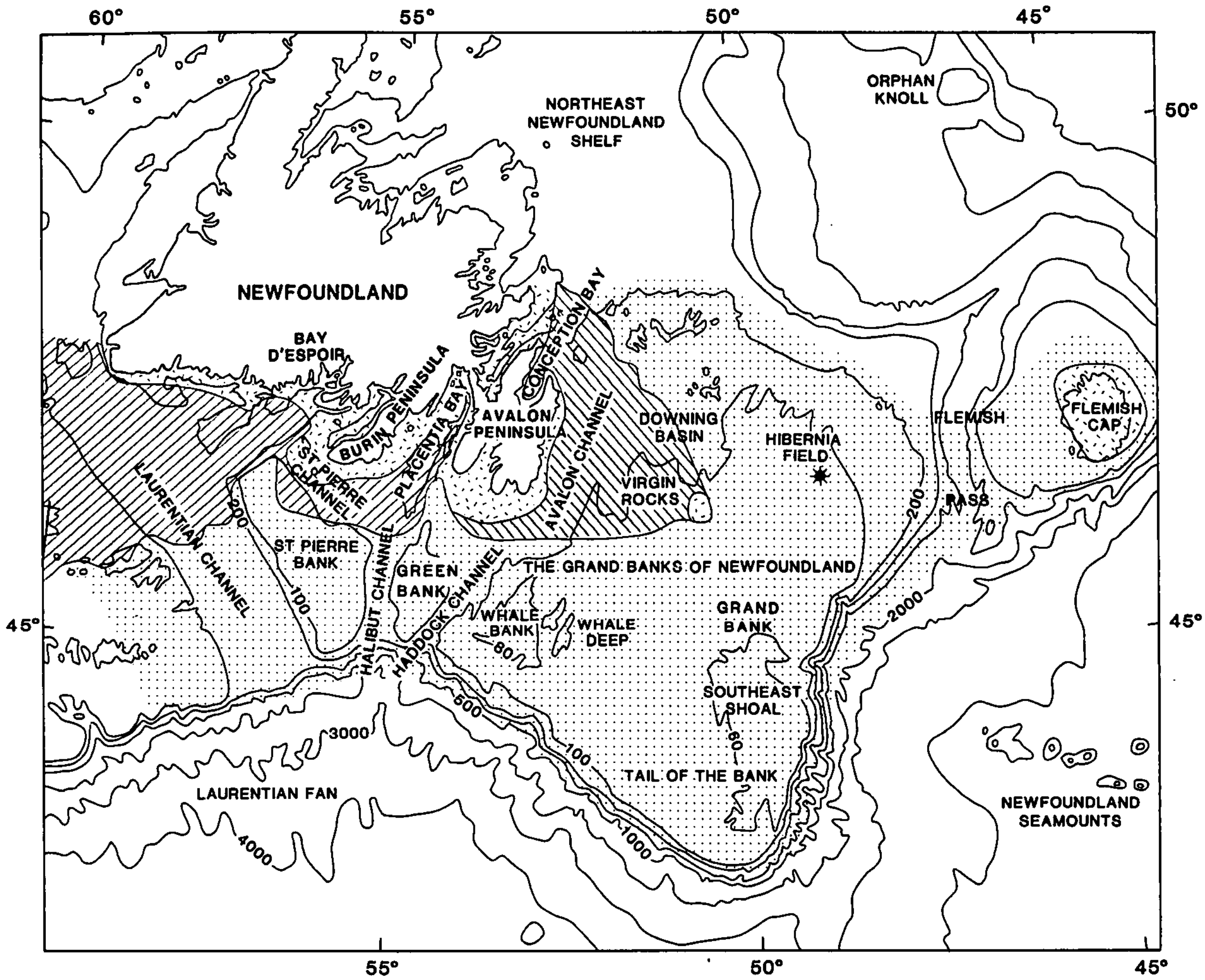


Figure 2.1 Place names on the Grand Banks of Newfoundland (from Piper et al. 1990).

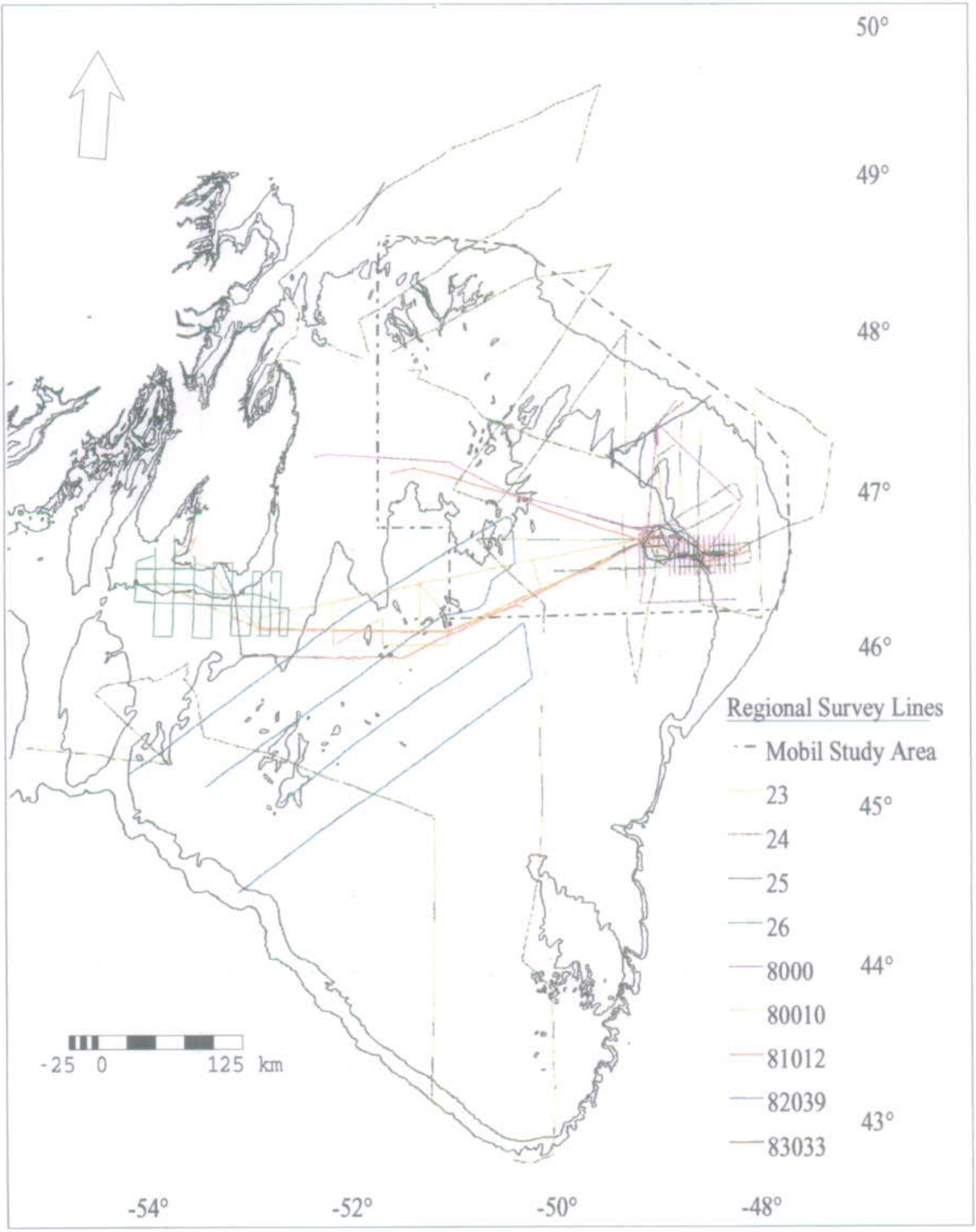


Figure 2.2 **Regional survey lines for cruises incorporated in the Mobil Ice Scour Catalogue (see Table 2.1 for cruise codes).**

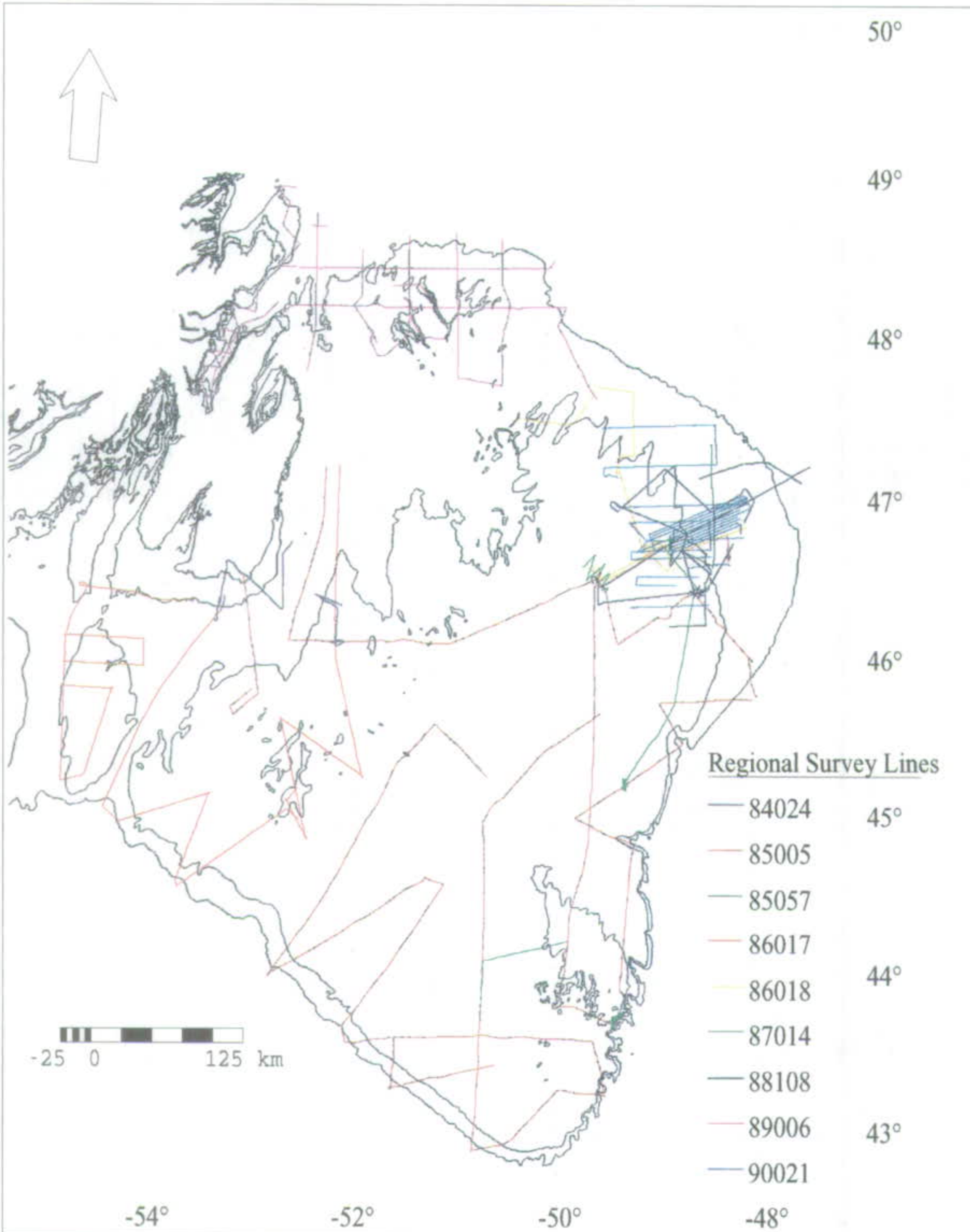


Figure 2.3 **Regional survey lines for the ESRF Repetitive Mapping Ice Scour Catalogue, the AGC Cruise 89-006 Database and the post-1983 AGC cruises (see Table 2.1 for cruise codes).**

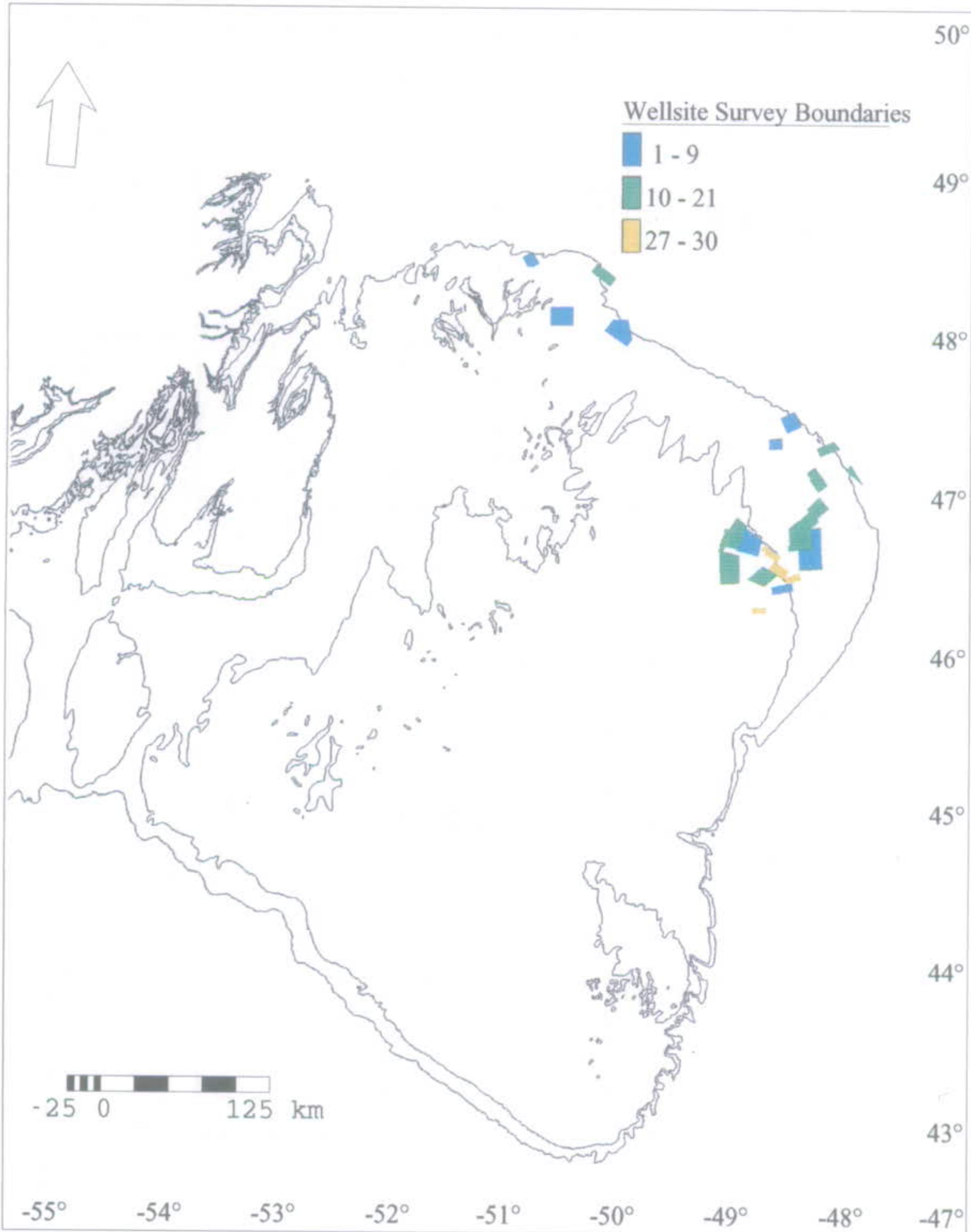


Figure 2.4a **Wellsite survey areas on northeastern Grand Bank. Green areas are those analysed for the Mobil Ice Scour Catalogue (1982), blue areas were added for the 1984 update and yellow areas indicate the post-1983 wellsite surveys (see Table 2.2 for cruise codes).**

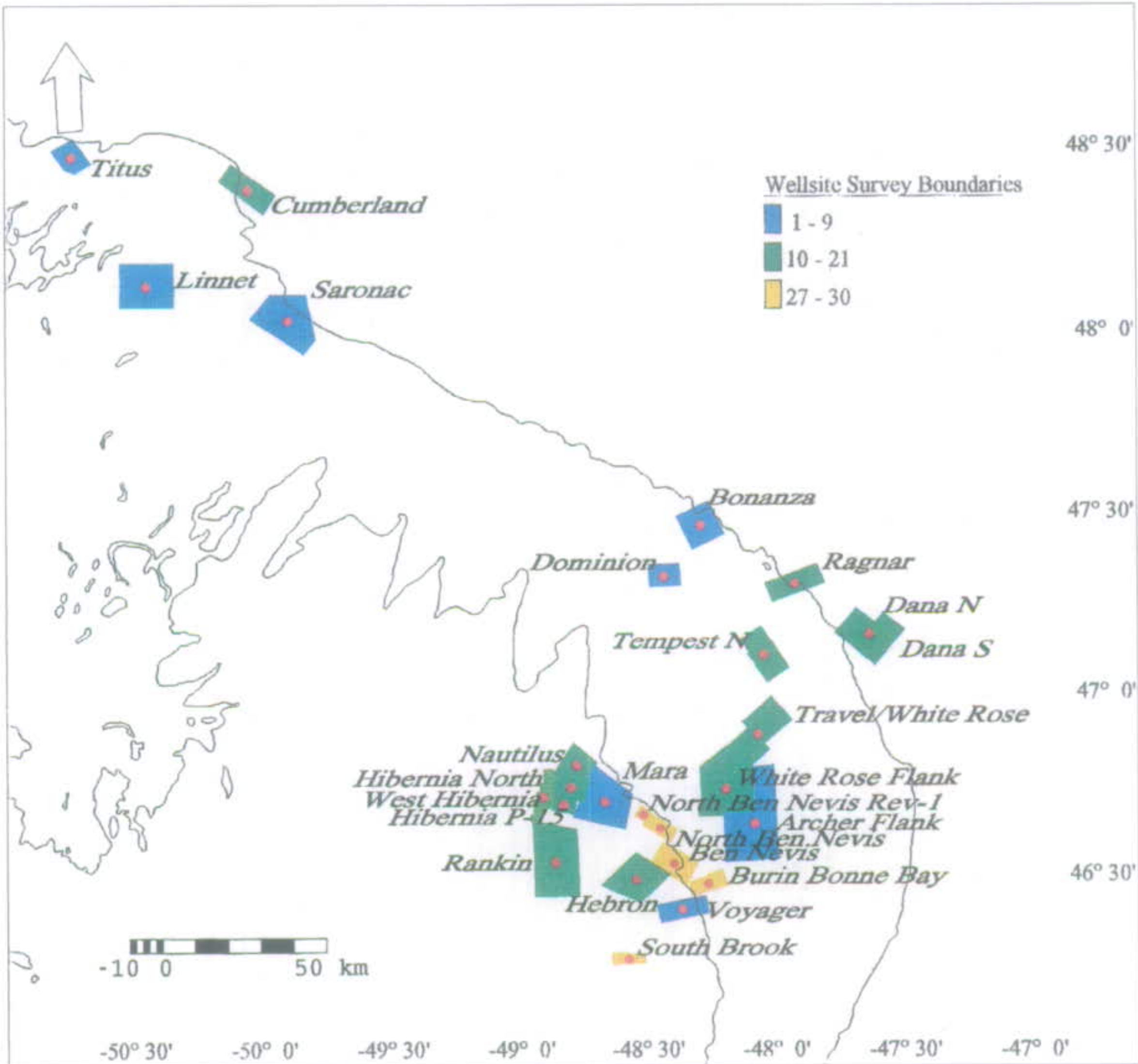


Figure 2.4b Individual wellsite survey boundaries on northeastern Grand Bank (see Table 2.2 for cruise codes).

3. CHARACTERISTICS OF THE ICEBERG PIT POPULATION

3.1 Exploratory Data Analysis

Previous statistical analyses of the ice scour population (e.g., NORDCO Ltd. 1982 and 1984, Geonautics 1989) have employed classical statistical analysis techniques to examine the characteristics of ice scours on the Grand Banks of Newfoundland. Classical analysis techniques use tools such as histograms to display and examine the data of interest (see Figure 3.1). Histograms clearly identify the position of the mode, and indicate if the distribution is unimodal, bimodal or skewed. However, the shape of the histogram is extremely sensitive to the width of the data interval and to the selected cutoff values. Other descriptive statistics such as the minimum, maximum, median and quartile values are also not readily detected from the histogram plot.

Exploratory data analysis techniques developed by Tukey (1977) provide an alternative method whereby the major characteristics of the data set are detectable in the graphical display of the data. One of the fundamental graphical tools in EDA is the box-and-whisker plot as illustrated in Figure 3.2. This method of data display permits the identification of outliers in the data set, non-linearities and skewness; these characteristics of the distribution can then be easily examined prior to the implementation of more complex statistical analysis techniques.

The box-and-whisker plot shown in Figure 3.2 is defined by two hinges, where the lower hinge (LH) is equivalent to the 1st quartile data value and the upper hinge (UH) is equal to the 3rd quartile value in the distribution. The hinges are split by the median (2nd quartile) value. Whiskers extend from the hinges to the inner fences. The extent of the inner fences is calculated as 1.5 times the inter-quartile range or H-Spread, defined as the difference between the upper and lower hinge values. The values for the lower inner fence (LIF) and the upper inner fence (UIF) are calculated as:

$$\text{LIF} = (\text{LH} - 1.5\ (\text{H-Spread})) \tag{3.1}$$

$$\text{UIF} = (\text{UH} + 1.5\ (\text{H-Spread})) \tag{3.2}$$

where

$$\text{H-Spread} = \text{UH} - \text{LH} \tag{3.3}$$

Any value beyond the inner fences (i.e., less than the lower inner fence or greater than the upper inner fence) is considered to be an outlier or an outside value (Figure 3.2). Extreme values are determined from the outer fences, where the lower and upper outer fences (LOF and LUF) are calculated as:

$$\text{LOF} = (\text{LH} - 3.0\ (\text{H-Spread})) \tag{3.4}$$

$$UOF = (UH + 3.0\ (H\text{-}Spread)) \quad (3.5)$$

Thus, any data values beyond the outer fences are considered to be extreme for the observed distribution. Extreme data values should be re-examined to determine if the data value is real or is the result of data interpretation or data entry errors.

Information derived from a box-and-whisker plot (commonly called a box plot) can be expressed as a seven-number summary:

1. lower outer fence (LOF)
2. lower inner fence (LIF)
3. lower hinge (LH)
4. median
5. upper hinge (UH)
6. upper inner fence (UIF)
7. upper outer fence (UOF)

Minimum, maximum and outside or extreme values can also be included in the letter summary to provide information on the range of larger (or smaller) values in the dataset. When the minimum value in the dataset is greater than the calculated lower fence values, the calculated values are replaced with the actual minimum data value. Similarly, when the maximum data value is less than the calculated upper fence values, the fence values are replaced with the data maximum. In either case, the data set may be lacking outside or extreme values.

Box plots can also be used to examine the shape of a distribution (e.g., symmetrical or asymmetrical). If the distribution is symmetrical the letter summaries will be evenly spaced, however, if the distribution is asymmetrical, spacing of the values above and below the median will be uneven when plotted on a graph.

Figures 3.1 and 3.2 illustrate the differences between a histogram plot and a box-and-whisker plot for the crater width data contained in the Grand Banks Scour Catalogue. The histogram shown in Figure 3.1 indicates that crater widths have a positively-skewed distribution. The positive skewness is also evident in the box plot presented in Figure 3.2, whereby the lower fence is shorter than the upper fence. Whenever the range of data values is limited at either end of a distribution, the whisker or fence length will appear shorter than when the range of values is larger.

On a box plot, the median is shown as a thick line between the upper and lower hinge values. The width of this line represents the 95% confidence interval for the median value. The width of the 95% confidence interval is computed by:

$$\text{median} \pm \frac{1.58\,(\text{H-Spread})}{\sqrt{n}} \qquad (3.6)$$

where n is the number of data values. If the median lines do not overlap when several box plots are presented on the same graph, it can be concluded ($\alpha = 0.05$) that the populations represented in each plot are distinct. For example, this method can be used to compare the physical characteristics of the iceberg pit populations in shallow and deep water depths.

In this chapter, the results derived from the box-and-whisker plots will be used to provide information on the characteristics of single or grouped distributions, to identify extreme values associated with crater dimensions and to examine the effects of water depth and geophysical analysis method on crater dimensions. In addition, a seven-number summary (LOF, LIF, LH, Median, UH, UIF and UOF) will be used to classify the crater data prior to regional mapping using GIS techniques.

3.2 Spatial Distribution of Iceberg Pits

The locations where iceberg pits have been observed on the Grand Banks of Newfoundland are shown in Figure 3.3. This figure indicates that the majority of iceberg craters have been recorded in three main areas: northeastern Grand Bank, Downing Basin and the southern portion of Avalon Channel. Very few pits have been seen in the shallower water regions of central and southern Grand Bank. The majority of the iceberg pit observations are associated with the wellsite surveys from the 1984 update to the Mobil Ice Scour Catalogue (see Table 2.9).

Figure 3.4 shows the areas covered by the cruises included in the Grand Banks Scour Catalogue. Although the greatest survey coverage is certainly over northeastern Grand Bank, several regional survey lines extend over the central and southern portions of the bank. This suggests that the limited numbers of crater observations on the bank tops may reflect a true lack of pit features, rather than an absence of data coverage. However, observational biases introduced by irregular data coverage and variations in data collection and analysis procedures cannot be eliminated without further, more detailed data analyses.

The range of water depths in which iceberg pits are observed is shown in Figure 3.5, including both box-and-whisker plots and the corresponding letter summary values. The shallowest pit was found in a water depth of 49 m, while the deepest was at 257 m. It should be remembered that the range of water depths associated with iceberg pits is probably limited by the extent of the available data, and does not reflect the true water depth limits of the entire iceberg pit population on the Grand Banks.

The median water depth in which iceberg pits have been found is 164 m, with 50% of the pit observations in deeper water and 50% in shallower waters. The water depth distribution is fairly symmetrical, with the lower hinge at 130 m and the upper hinge at 194 m (1st and 3rd quartile values, respectively). The calculated fence values all lie outside of the actual minimum and maximum water depth values, thus, the GBSC does not contain any iceberg pits occurring in extreme water depths.

Figure 3.5 also shows the water depth data sub-divided into two populations, representing those pits occurring in shallow waters less than 110 m and those pits found in deeper waters. This breakdown represents the postulated change in the age of the pit population (modern vs. combined modern and relict) and changes in the pit identification procedures (see Section 2.0). Of the total of 1763 iceberg pits in the Grand Banks Scour Catalogue, 233 occur in water depths less than 110 m, while the remaining 1530, or 87%, are found in deeper waters. This topic will be discussed in more detail in Section 3.5 of this report.

3.3 Physical Characteristics of Iceberg Pits

Of the total of 1763 iceberg pits in the Grand Banks Scour Catalogue, 897 have a measured value recorded in the crater depth field (Section 2.2.4). Of those craters with depth measurements, 2 have depths entered as less than the resolution of the sub-bottom profiler system. The remaining 895 craters have been used to examine the characteristics of the distribution of crater depths as measured on the Grand Banks of Newfoundland.

Figure 3.6 gives box-and-whisker plots together with the letter summary values for the entire dataset of iceberg pit depth values, as well as separately for the deep- and shallow-water pit populations. For the entire population of iceberg pits with measured depth values, the median depth is 2.0 m, with the lower and upper hinge values at 1.5 m and 2.5 m, respectively. Thus, 50% of the measured pit depths lie between 1.5 and 2.5 m (lower and upper hinges, corresponding to 1st and 3rd quartile values), with 75% of the depth measurements less than 2.5 m (upper hinge). Thirty-two pits can be considered outliers, with depths greater than the upper inner fence value of 4.0 m. Another 15 pits have extreme depths exceeding the upper outer fence value of 5.5 m. Of the pits with extreme depths, Bowers Pit is the most notable with a depth of 10.0 m (see Section 2.2.3).

Figure 3.6 also shows the crater depth distributions for the shallow- and deep-water pit populations, based on the imposed sub-division at 110 m water depth. A comparison between the box-and-whisker plots and the letter summaries for the two pit populations suggests that the shallow-water pits are somewhat less deep than the deep-water pits (median values of 1.5 m and 2.0 m, respectively). However, the small sample size (n = 24) for the shallow-water pits leads to a large uncertainty in statistical values such as the median; this is reflected in the width of the 95% confidence interval shown on each box plot. The large H-spread for the depths of the shallow-water pit population may also be an artifact of the small sample size.

The statistics derived from the iceberg pit depth data should be interpreted with caution; limitations associated with the measurement of crater depth are discussed in Section 2.2.4 of this report. The largest single source of error in the measurement of pit depth is likely due to the position of the survey track line relative to the deepest part of the pit feature. Unless the deepest part of the pit is transected by the relatively narrow swath of the sub-bottom profiler system, the maximum pit depth will be underestimated. The Bowers Pit example summarized in Table 2.7 illustrates the range of measured pit depths associated with different surveys of a single seabed feature.

The exploratory data analysis techniques developed by Tukey (1977) and used in this report are generally applied to univariate, non-spatial data. However, much of the data used in this study has a spatial component (e.g., pit location). For this project, the EDA approach developed by Simms (1993) has been used to map the distribution of outliers and other patterns that may exist in the crater database. The methodology is adapted from Vellman and Hoaglin (1981), whereby exploratory data analysis techniques are integrated with the mapping capabilities of GIS to examine the characteristics of iceberg craters on the Grand Banks of Newfoundland.

There are two steps in the EDA analysis: firstly, box-and-whisker plots are used to derive summary statistics that help to identify extreme events; secondly, the results of the EDA are used to classify information stored in the GIS for the mapping of individual crater parameters. For example, the letter summary values shown in Figure 3.6 can be used to sub-divide the iceberg pit population into classes based on crater depth. Class intervals are set according to the letter summaries, with the following sub-divisions for the crater depth data:

1. minimum to lower hinge
2. lower hinge to median
3. median to upper hinge
4. upper hinge to upper inner fence
5. upper inner fence to upper outer fence (outside values)
6. upper outer fence to maximum (extreme values).

Each iceberg pit depth class can then be plotted as shown in Figure 3.7. This approach allows any spatial variations in pit depth to be easily assessed.

Crater width data have been assessed in a similar manner. Figure 3.8 shows the results of the EDA for the available width data, for the entire population of iceberg pits with width measurements and for both deep- and shallow-water pit populations. The median pit width is 60 m, with 50% of the measured pit widths between 36 and 90 m (lower and upper hinge values). 26 pits represent outliers, with widths exceeding 171 m. An additional four pits have extreme widths exceeding 252 m, with a maximum recorded pit width of 350 m.

Of the total of 1690 pits with measured width values, 227 occur in water depths of less than 110 m. The shallow-water pit population appears to be somewhat smaller in size than the deep-water pit population, with median pit width values of 30 m and 65 m, respectively. The limitations associated with the measurement of pit width are discussed in Section 2.2.4 of this report.

3.4 Geophysical Data Analysis Method

The methods used to identify and measure the characteristics of iceberg pits from the available geophysical data records are summarized in Section 2.2 and in Table 2.1, Table 2.2 and Table 2.3 of this report. For the original version of the Mobil Ice Scour Catalogue (regional lines and wellsite surveys), iceberg pits were included in the catalogue when seen on the sub-bottom profiler data. Side scan sonar records were used only to confirm the nature of the ice-contact feature (pit or scour).

In the 1984 update to the Mobil Ice Scour Catalogue, pits were included in the database when observed on either the sub-bottom profiler data or on the side scan sonar records. Regional survey lines, pipeline surveys and wellsite surveys appear to have been analysed in the same manner. All observed pits, regardless of water depth, appear to have been included in the ice scour database.

For the remainder of the data sources included in the Grand Banks Scour Catalogue (AGC Cruise 89-006 Database, ESRF 4000 Series Database, GBS Mosiac Site, post-1983 wellsites and post-1983 AGC cruises), pits were recorded only when visible on the side scan sonar records. Features seen only on sub-bottom profiler data were not included. Only those pits that were "fresh-looking" were included in the GBSC for water depths greater than 110 m.

In order to examine the potential for biases in the database resulting from the type of geophysical data used in pit identification, the three classes of data were examined separately. Figure 3.9 shows the water depth range in which iceberg pits were found for each category of data analysis. The majority of observed pits (63%) are associated with the 1984 update to the Mobil Ice Scour Catalogue; these pits were recorded when seen on either the sub-bottom profiler or the side scan sonar data. This class of iceberg craters is associated with a median water depth of 170 m, with a similar water depth distribution as for the entire population of iceberg pits (see Figure 3.5).

The pit population identified solely from the sub-bottom profiler data (18%) is associated with deeper water depths, while the pit population derived from side scan sonar records alone (19%) is biased towards shallower waters. The shallow-water bias of the pit population derived from side scan sonar records is not surprising when it is considered that, in water depths greater than 110 m, only features appearing "fresh" on the side scan sonar records were included in the pit database.

A comparison of the crater depth distributions, using pit depth data classified by geophysical data analysis method, is presented in Figure 3.10. This comparison shows no discernible differences in the distributions of measured crater depths between the three analysis methods. This is an expected result, in that, regardless of the data set used to identify pit features, crater depth measurements can only be obtained from sub-bottom profiler data. The wider H-Spread associated with the side scan sonar data set is likely an artifact of the small sample size.

3.5 The Modern Iceberg Pit Population

As discussed in Sections 1.0 and 2.0 of this report, pit age is an important factor in the assessment of the frequency of pit formation and thus the risk to seabed structures. Although observed pit populations are thought to include both modern and relict populations, it has been previously assumed that:

- ice-contact features found below about 200 m water depth represent relict features,
- ice-contact features found above about 110 m water depth represent the modern, post-glacial population, and
- features found between 110 m and 200 m represent a mixture of modern and relict populations.

In addition to providing a general description of the distribution and characteristics of the iceberg pit population on the Grand Banks of Newfoundland, the statistical analyses presented in this section have been oriented towards addressing the issue of pit age. In particular, separate analyses of the pit dimension variables (depth and width) have been conducted on those pits found above and below 110 m water depth (Figures 3.6, 3.7 and 3.8). These analyses were based on the hypothesis that relict pits may be larger and deeper than those formed in relatively modern times.

In terms of pit depth, no statistically-significant difference was found between the shallow- and deep-water pit populations (Figure 3.6). However, only 24 depth measurements were available for pits located in water depths of less than 110 m; thus the confidence in the median value for this distribution is relatively low. In terms of crater width, the median value for deep-water pits is roughly double that for shallow-water pits. However, this difference may be related to inaccuracies introduced by the measurement process, since crater widths for many of the deep-water pits were measured from sub-bottom profiler data (apparent width as compared to true width from corrected side scan sonar measurements).

Further analyses on the pit dimension data were conducted by binning the available crater depth and width data into 20 m water-depth intervals. Data from each depth interval were then analysed separately for median values, upper and lower hinges, etc. The results of these analyses are plotted in Figure 3.11 and 3.12. The crater depth data (Figure 3.11) indicate a fairly constant median value in water depths below about 140 m, followed by an increase from 1.0 m to 2.0 m at 180 m water depth, a subsequent decrease, and then a further increase to 2.5 m at 260 m water depth. Although weak, a general trend towards increasing crater depth with increasing water depth seems to be present in the data.

The variation in crater width with water depth is shown in Figure 3.12. A somewhat stronger trend exists than that seen in the crater depth data, with crater widths increasing fairly consistently with increasing water depth. An interesting feature of both curves is a zone of constant or decreasing crater depth and width values between water depths of roughly 180 and 220 m.

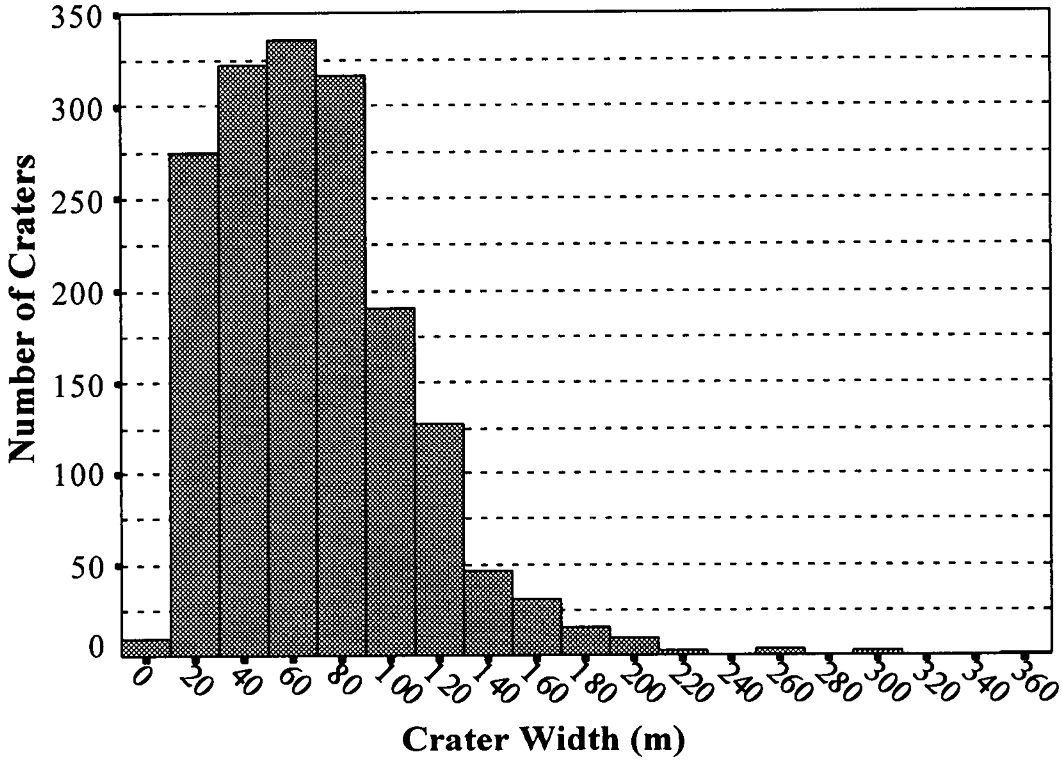


Figure 3.1 **Width distribution for iceberg craters included in the Grand Banks Scour Catalogue.**

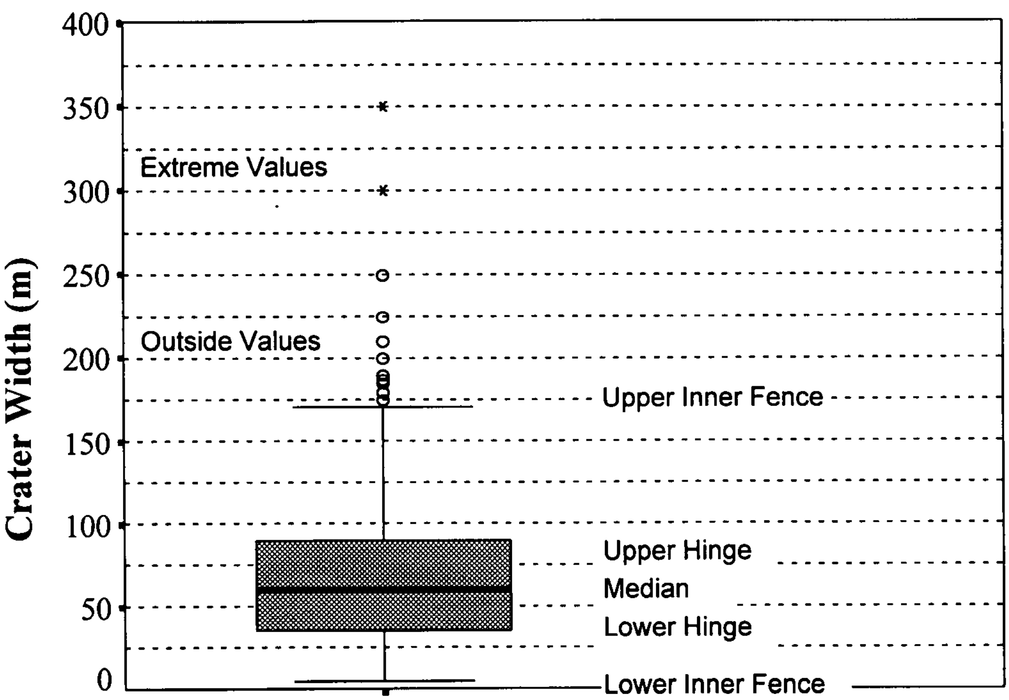


Figure 3.2 **Box-and-whisker plot for crater width data in the GBSC.**

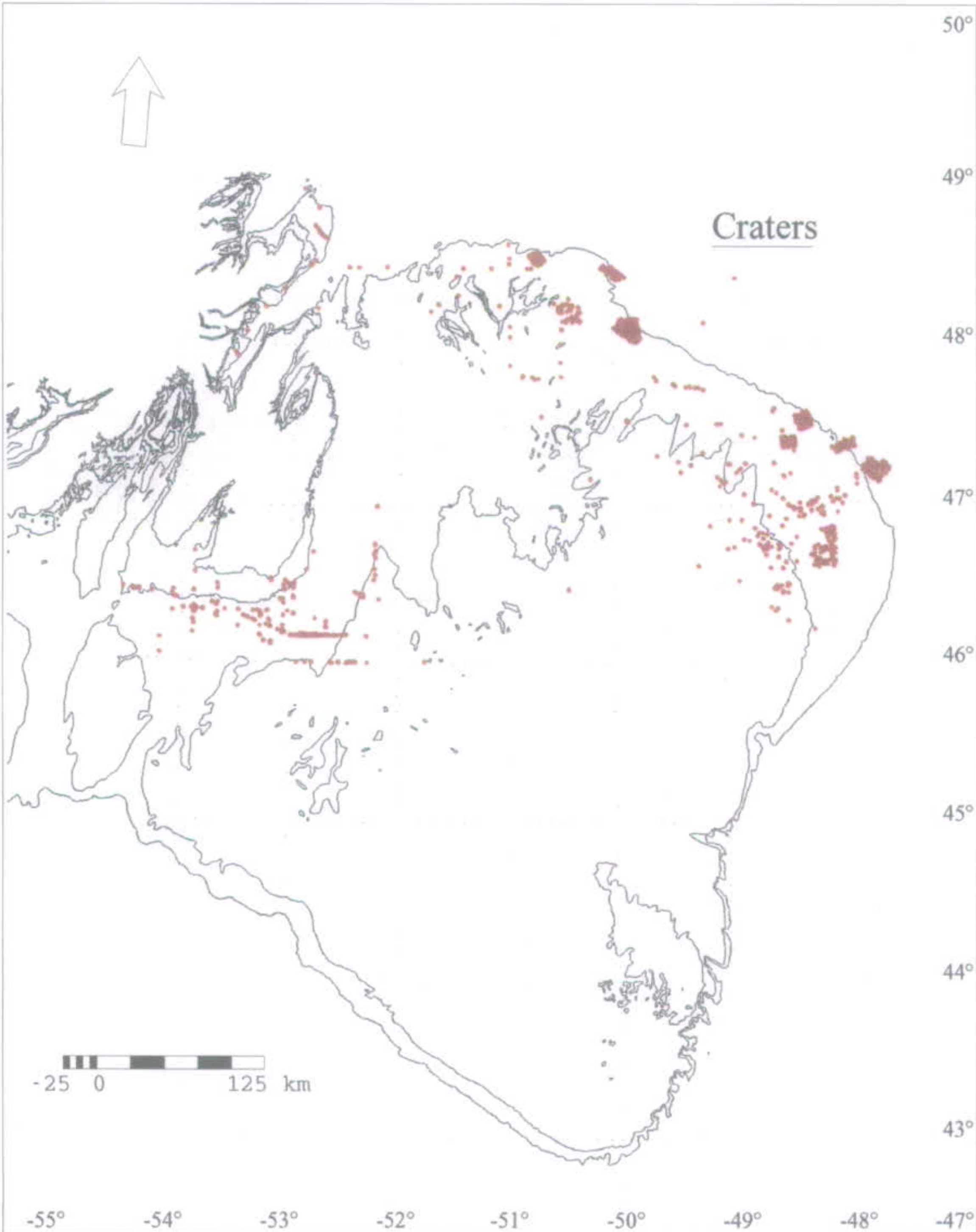


Figure 3.3 Iceberg crater observations on the Grand Banks of Newfoundland.

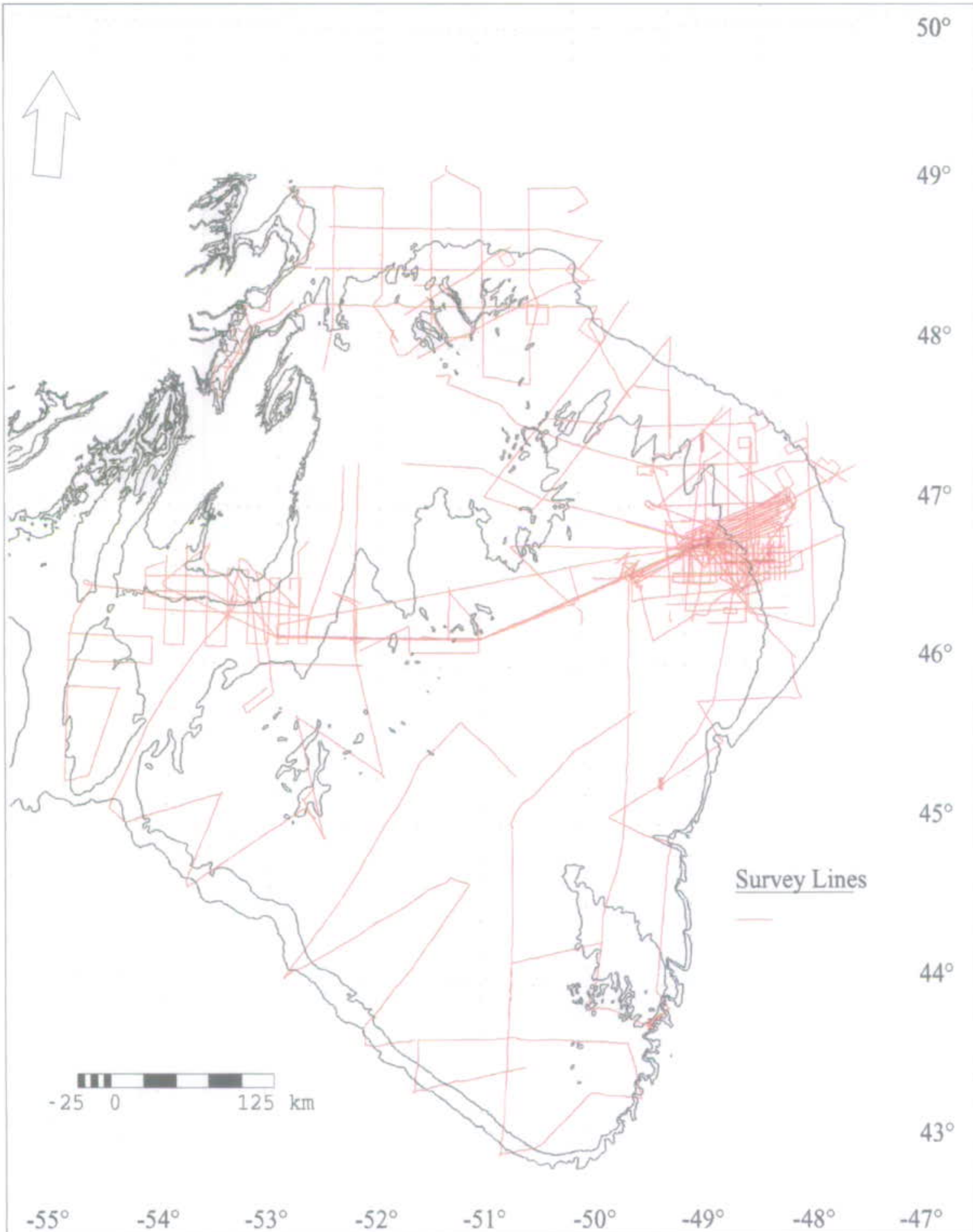
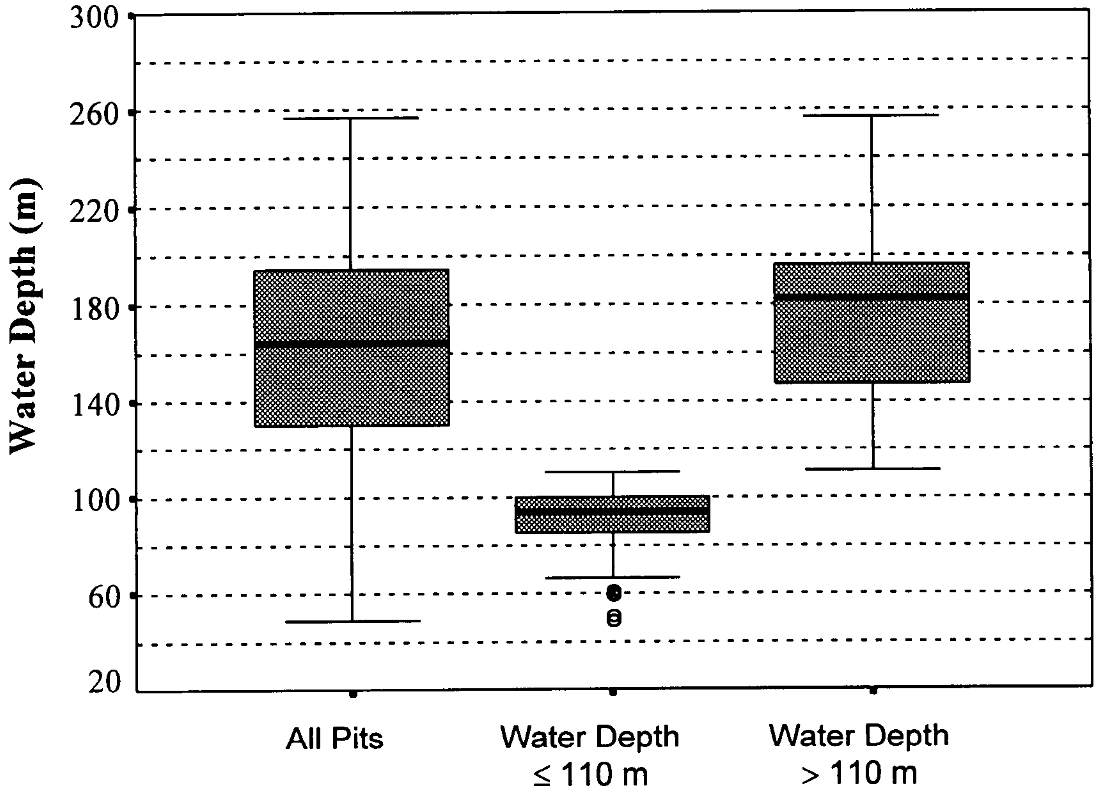
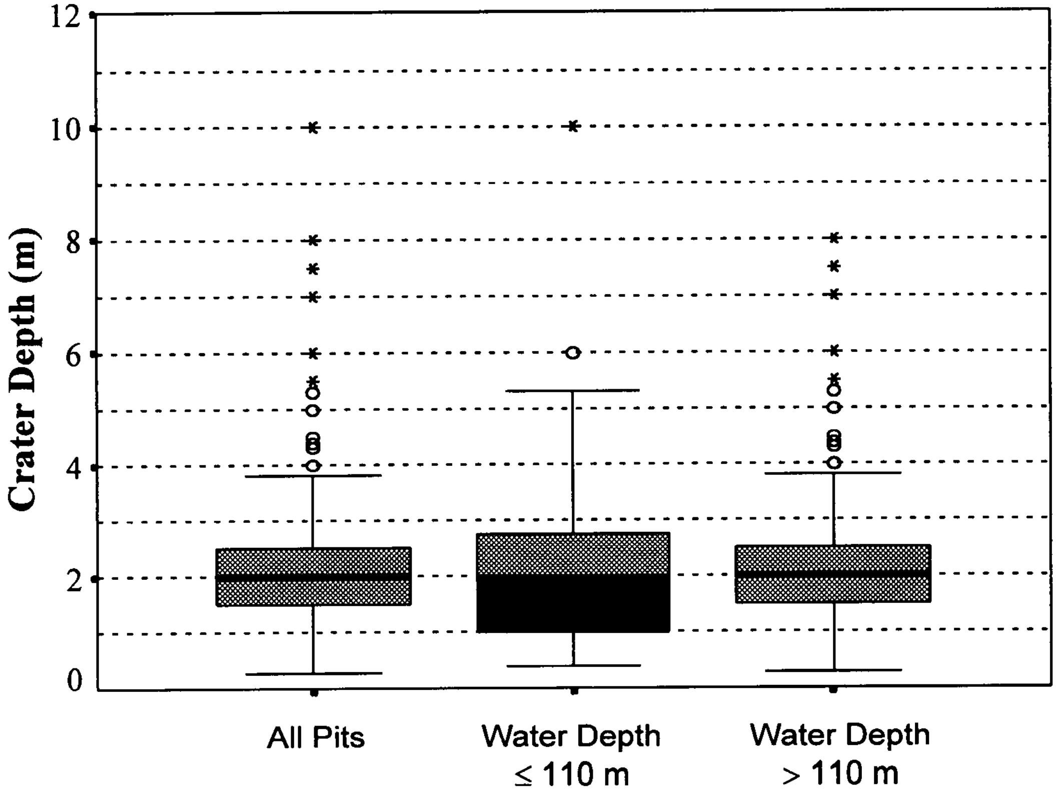


Figure 3.4 Geophysical data coverage on the Grand Banks of Newfoundland.



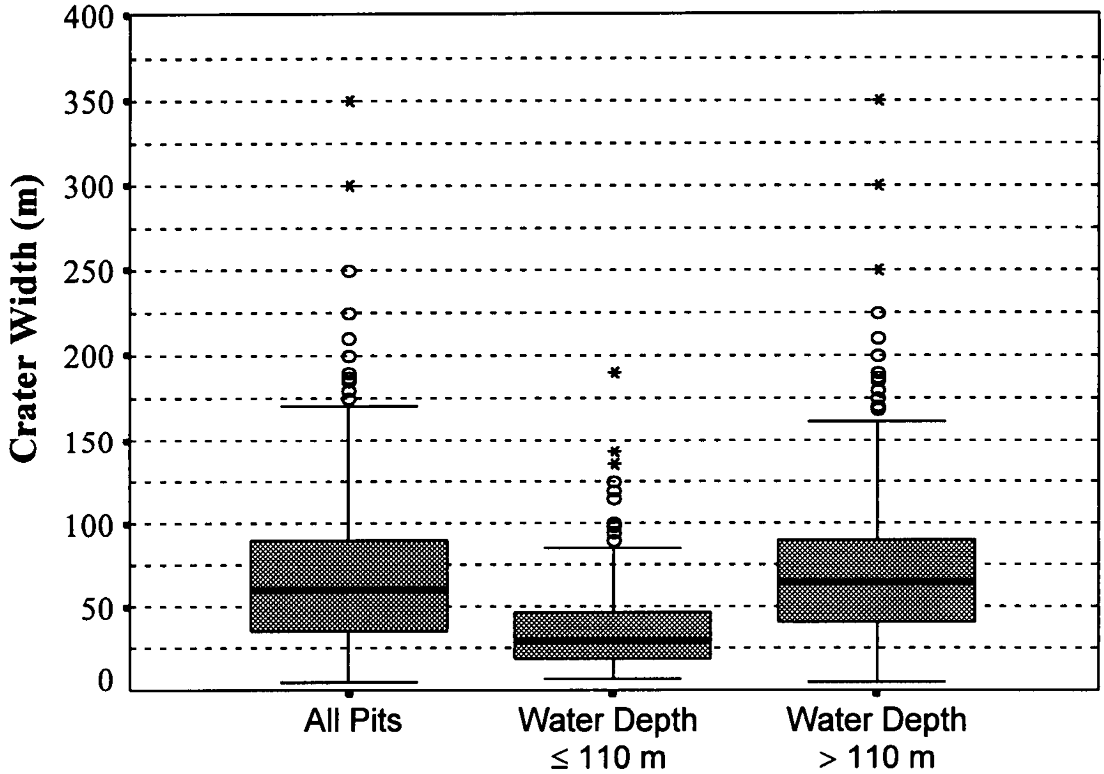
Letter Summary	All Pits	Water Depth ≤ 110 m	Water Depth > 110 m
Minimum	49.0	49.0	111.0
Lower Outer Fence	49.0	49.0	111.0
Lower Inner Fence	49.0	62.5	111.0
Lower Hinge	130.0	85.0	147.0
Median	164.0	94.0	182.0
Upper Hinge	194.0	100.0	196.0
Upper Inner Fence	257.0	110.0	257.0
Upper Outer Fence	257.0	110.0	257.0
Maximum	257.0	110.0	257.0
Sample Size	1763	233	1530

Figure 3.5 Water depths at which iceberg pits are observed.



Letter Summary	All Pits	Water Depth ≤ 110 m	Water Depth > 110 m
Minimum	0.3	0.4	0.3
Lower Outer Fence	0.3	0.4	0.3
Lower Inner Fence	0.3	0.4	0.3
Lower Hinge	1.5	1.0	1.5
Median	2.0	1.5	2.0
Upper Hinge	2.5	2.8	2.5
Upper Inner Fence	4.0	5.4	4.0
Upper Outer Fence	5.5	8.0	5.5
Maximum	10.0	10.0	8.0
Sample Size	895	24	871

Figure 3.6 Distribution of measured depths for all craters, shallow-water craters and deep-water craters.



Letter Summary	All Pits	Water Depth ≤ 110 m	Water Depth > 110 m
Minimum	5.0	7.0	5.0
Lower Outer Fence	5.0	7.0	5.0
Lower Inner Fence	5.0	7.0	5.0
Lower Hinge	36.0	19.0	41.0
Median	60.0	30.0	65.0
Upper Hinge	90.0	47.0	90.0
Upper Inner Fence	171.0	89.0	163.5
Upper Outer Fence	252.0	131.0	237.0
Maximum	350.0	190.0	350.0
Sample Size	1690	227	1463

Figure 3.8 Distribution of measured widths for all craters, shallow-water craters and deep-water craters.

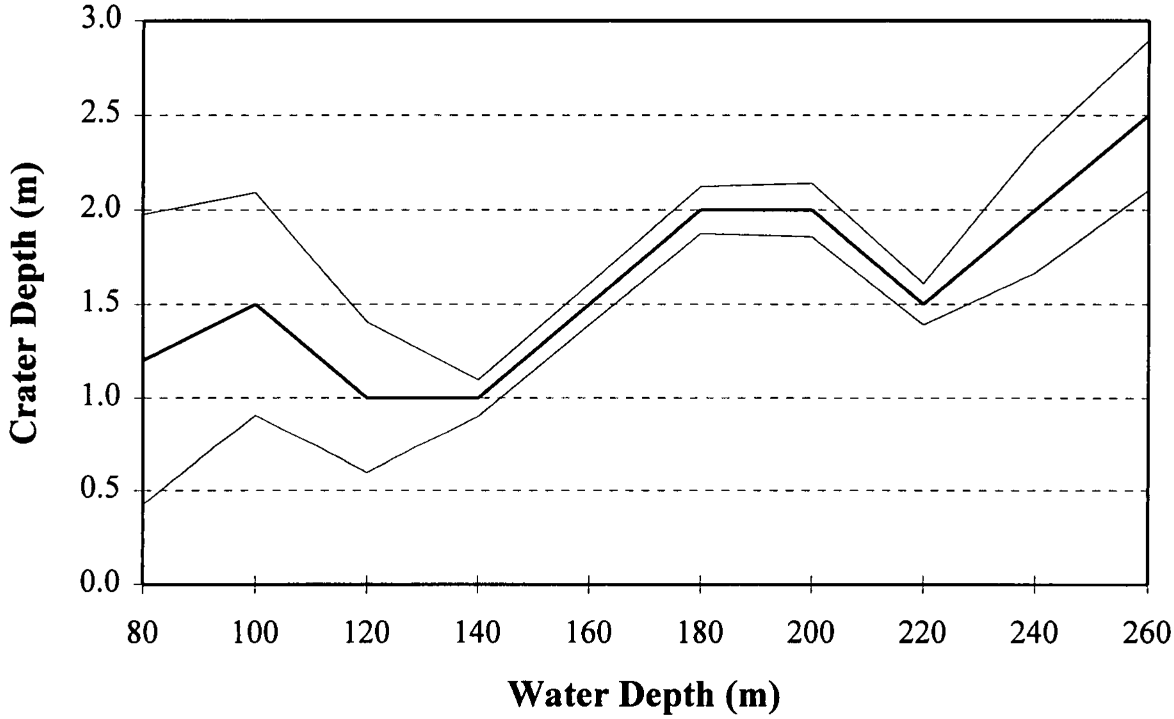


Figure 3.11 Variation in median iceberg pit depth with water depth (calculated by binning data into 20 m water depth intervals). Lighter lines represent 95% confidence intervals.

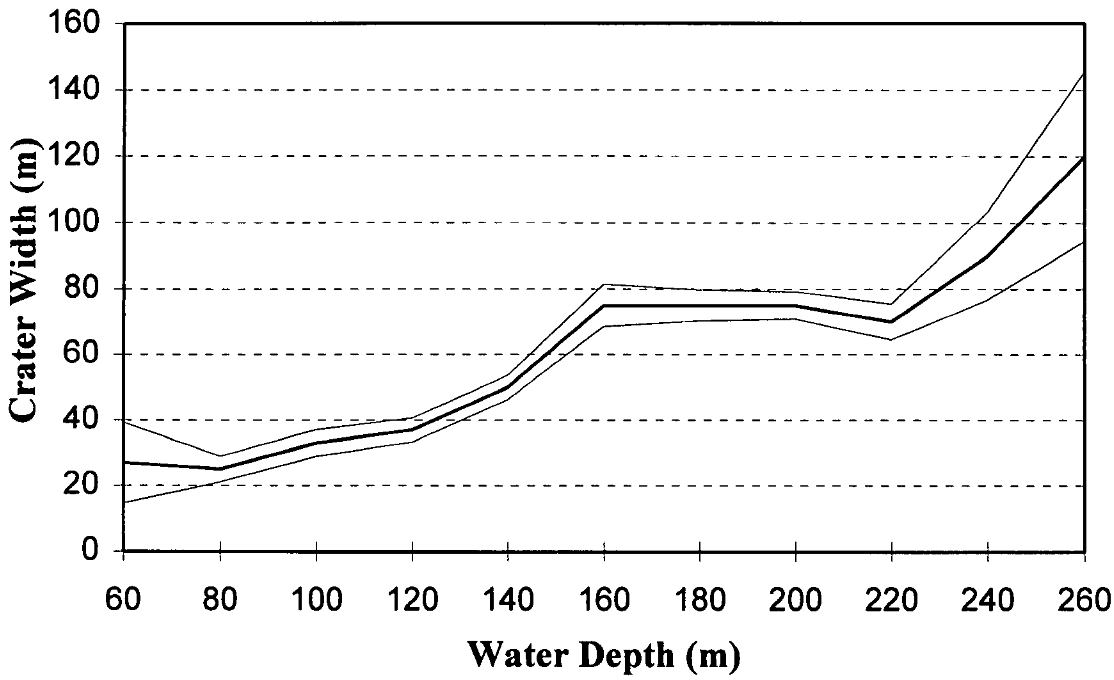


Figure 3.12 Variation in median iceberg pit width with water depth (calculated by binning data into 20 m water depth intervals). Lighter lines represent 95% confidence intervals.

4. ENVIRONMENTAL FACTOR DATABASE

4.1 Introduction

The environmental factor database has been developed to include many of the parameters thought to potentially influence the formation, characteristics and persistence of iceberg pits on the Grand Banks of Newfoundland. Potentially important factors include water depth, ocean currents, wave conditions, tidal range, sediment type and grain size, geotechnical properties of the seabed, frequency of iceberg grounding events, shape of grounding icebergs and other parameters not listed here.

The relevant environmental parameters can be broadly grouped into three main categories: physical oceanography, seabed geology and iceberg characteristics. The following sections summarize the regional setting for each of these categories, the types of data available, and the particular environmental parameters included in the environmental factor database. In reading this material, it should be recognized that the actual environmental parameters suitable for use in this study are limited by the amount of available data, particularly in terms of the regional data coverage requirements of this project.

4.2 Physical Oceanography

The oceanographic processes that have been identified as potentially influencing iceberg pits on the Grand Banks of Newfoundland are those that affect iceberg movement and the mobility of seabed sediments. Iceberg movement is driven primarily by ocean currents, with wind forcing playing a relatively minor role in determining iceberg trajectory. Iceberg movement is limited by the local water depth; if the iceberg draft exceeds the available water depth, grounding occurs. The available water depth is determined by a combination of local bathymetry and tidal fluctuations, and may also be impacted by atmospheric events (i.e., storm surge). Ocean currents and water depth parameters are discussed in more detail in the following material; iceberg drafts are discussed in Section 4.4.2 of this report.

The long-term persistence of any feature on the seabed is impacted by local sedimentary processes. Over time, infilling of any seabed depression may occur in response to gross sediment deposition or localized transport or reworking of the bottom sediments. Sediment transport processes are strongly related to the strength of ocean currents, and to the characteristics of the bottom sediments. Storm events and the associated surface waves also play an important role in reworking and remobilization of seabed sediments. Surface wave conditions on the Grand Banks of Newfoundland will be discussed in this section; separate parameters developed for this project to more accurately reflect the mobility of seabed sediments are described in Section 4.3.5.

200 m isobath. The relatively weak inshore branch, carrying roughly 10% of the transport, follows the Newfoundland coastline into Avalon and Haddock Channels. The seaward extent of the inshore branch of the Labrador Current is roughly bounded by the 100 m isobath (Greenberg and Petrie 1988).

Mean current speeds in the offshore branch of the Labrador Current are typically on the order of 0.2 to 0.3 m s^{-1}, but have been observed to reach 0.6 m s^{-1} on the eastern slope of Grand Bank. In the offshore branch, mean current speeds typically far exceed the time-varying component of flow. Mean current speeds in the inshore branch of the Labrador Current are generally weaker, with speeds up to 0.2 m s^{-1} and with the fluctuating component of flow similar in magnitude to the mean. Over the bank tops, currents are relatively weak (0.02 to 0.1 m s^{-1}), generally southwards and dominated by the variability (Petrie and Anderson 1983).

The mean circulation patterns on the Grand Banks of Newfoundland have been modelled by Greenberg and Petrie (1988), using a two-dimensional, depth-averaged numerical model. Model results as calculated on a 4' by 4' grid are presented in Figure 4.4. These results were found to agree well with previous observations of circulation patterns in the region, with the exception of the currents through Flemish Pass and over Flemish Cap. The net westerly flow direction over the bank top also contradicted previous interpretations of a generally weak, southward flow (see Petrie and Anderson 1983); however, wind effects not included in the model formulation could be responsible for this difference in flow direction.

Atmospheric forcing, in the form of storm events and the associated wind stress applied to the sea surface, can generate large currents on continental shelves in addition to surface waves (Section 4.2.3). Atmospheric events typically have a time scale of from 2 to 8 days, representing the average interval between the passage of weather systems. A shift in the wind will also excite inertial motions; these are a resonant response of the ocean associated with the rotation of the earth. The period of inertial motions is determined by the latitude and decreases in a northward direction, ranging between roughly 18 and 15.5 hours over the Grand Banks of Newfoundland and the Northeast Newfoundland Shelf.

Storm-driven currents are described by Petrie (1993), who used a two-dimensional, depth-averaged numerical model to calculate the currents and sea-level variations associated with 28 severe storms over the Grand Banks of Newfoundland. The 28 storms are part of the database of severe storms chosen for their potential to generate large surface waves (Section 4.2.3). The limited current meter data available for model verification suggested that model results are most accurate in the winter months, when water column stratification is weak.

4.2.3 Surface Waves

Surface waves are potentially an important factor in both the formation and persistence of iceberg pits on the seabed of the Grand Banks of Newfoundland. With respect to the formation of iceberg pits, oscillatory wave loading on a grounded iceberg may lead to progressive soil failure in the underlying seabed. With regards to the persistence of iceberg pits on the seabed over time, wave action may play a dominant role in the reworking of bottom sediments and the subsequent degradation of ice-contact features. Wave action may be particularly important in seabed reworking on the bank tops, where wave-induced oscillatory currents are strongest and other current components are relatively weak.

For this project, surface wave data were obtained from a hindcast study of extreme wind and wave conditions for the east coast of Canada (Canadian Climate Centre 1991). In this hindcast study, available wind and wave measurements were used together with numerical models in order to estimate extreme wave conditions on a regional basis. The use of numerical models allowed limited, site-specific wave measurements to be extended over a regional grid. The methodology used in the hindcast study will be summarized in this section, followed by a description of how the wave data were used in the iceberg pit project.

In the hindcast study described by the Canadian Climate Centre (1991), a database of severe storms affecting Georges Bank, the Scotian Shelf and the Grand Banks of Newfoundland was developed from a variety of data sources. Storms were selected for inclusion in the database through the use of indirect estimates of the potential for generation of large surface waves (i.e., sea-level pressure gradients, storm central pressure, etc.). Selected storms were then ranked according to severity, based on a combination of meteorological properties of each storm and actual measurements of surface wave conditions. A total of 532 storm events covering the time period from 1957 to 1988 were considered.

The 68 most severe storms affecting eastern Canadian waters were chosen for hindcast modelling. Wind fields were modelled for each storm using a combination of data analysis and numerical modelling techniques. Wave fields were modelled using the Ocean Data Gathering Program (ODGP) Spectral Ocean Wave Model, a deep-water fully-directional spectral wave model. For each of the 68 severe storms, directional wave spectra were produced every 2 hours for each grid point in the model domain (0.625° latitude by 1.25° longitude for the Grand Banks, Scotian Shelf and Georges Bank regions).

Model results for both wind and wave hindcasts were compared against actual measurements for 10 pre-selected storms where good data coverage was available. The verification analyses indicated that the wave model tended to overpredict wave heights at

Miller 1986a and 1986b, Grant et al. 1986, King and Fader 1986, and many others). The following paragraphs summarize the regional surficial geology and geological history of the Grand Banks as interpreted by these researchers, the implications for this project, and the available data and data limitations.

The Grand Banks of Newfoundland are a series of shallow banks (St. Pierre Bank, Green Bank, Whale Bank and the largest, Grand Bank) separated from the Newfoundland coastline by the deep Avalon and St. Pierre Channels. The banks are separated from each other by the transverse troughs of Halibut Channel, Haddock Channel and Whale Deep (see Figure 2.1). The broader depression of Downing Basin lies between Grand Bank and the Northeast Newfoundland Shelf. Flemish Cap is a submarine knoll isolated from northeastern Grand Bank by Flemish Pass, a deep submarine saddle over 100 km wide.

The central, southern and eastern portions of the Grand Banks of Newfoundland are underlain by harder strata of Tertiary or early Quaternary age (acoustic bedrock), with a relatively thin cover of mixed sediments, consisting primarily of sands and gravels. The cover layer of sediments reach a maximum thickness of 15 m in sand ridges, prevalent over much of central and southern Grand Bank. Thicker Quaternary sediment deposits, up to 400 m deep, fill sub-glacial meltwater channels incised into the Tertiary strata on the outer shelf regions, particularly the eastern edge of Grand Bank. These channels appear to represent headward extensions of the major shelf-edge submarine canyons.

Filled channels also appear beneath St. Pierre, Whale and Green Banks, with shallower channels found less frequently in the Hibernia area. Channels in the Hibernia region appear to be filled with conformable glaciomarine sediments overlying possible till deposits. Haddock and Halibut Channels, the major transverse troughs between the banks, are infilled with at least three tills interbedded with glaciomarine sediments. On the southwest edge of Grand Bank, from the Tail of the Bank to Whale Bank, a surficial sandy mud tops a complex, 30 m thick layer of stratified glaciomarine sediments and till.

The underlying, harder strata on the central, southern and eastern portions of Grand Bank appears as continuous, coherent layers dipping slightly in a seaward direction, with widespread occurrence of wedge-shaped bodies of prograded sandy sediment. The wedge-shaped bodies of prograded sediments are thought to represent shelf-edge outbuilding during Tertiary or early Quaternary times of lowered sea level. A major regional unconformity separates the top of the older strata from the overlying Quaternary sediments; this unconformity is generally flat with little relief. The unconformity surface itself is thought to consist of stiffer sediments than both the underlying Tertiary materials and the overlying sands and gravels.

In contrast, the harder surface underlying the surficial sediments on the inner part of Grand Bank is far more complex. The inner bank includes the basins of Whale Deep and Downing Basin, as well as the bedrock highs represented by Virgin Rocks and Eastern character at the 107 m isobath, with mixed sands and gravels above this depth and medium to fine sand below. This transition marks the boundary between the Grand Banks Sand and Gravel and the Adolphus Sand formations described in the following section, and may represent either the approximate position of the low sea level stand or the maximum depth of storm-related sediment reworking (depth of wave base).

A proposed sea level curve for northeastern Grand Bank is shown in Figure 4.8, based on the age and water depth of shells. This curve indicates a low stand of sea level at about the 100 m isobath, at about 18 000 years before present. The depth of the wave base is postulated at 20 m below sea level in this figure, giving a maximum depth of seabed reworking at 120 m below the present-day sea level.

4.3.2 Surficial Geologic Units

The modern-day sediment supply to the Grand Banks is relatively low, with only minor inputs to the continental shelf through river discharge. Petrographic analysis of Holocene gravels has shown that ice-rafting from the north is also a source of sediment to Grand Bank. Sediment cover over much of the banks is thin, and bank tops may be erosional, with areas of modern sediment deposition limited primarily to basins.

As discussed previously, the majority of the surficial deposits on the banks have largely been formed during glacial recession, creating till sheets overlain by proglacial silts. Many of these deposits have been reworked and sorted during shelf transgression, as the rising post-glacial sea level caused the coastal zone to move inwards across what is now the continental shelf. The surface veneer on the bank tops is subject to ongoing reworking by both ice scouring processes and the impacts of major storm events.

The surficial sediments on the Grand Banks of Newfoundland have been divided into five main geologic units representing deposit origin and characteristics: Grand Banks Drift, Downing Silt, Adolphus Sand, Grand Banks Sand and Gravel, and Placentia Clay. Of these five units, the first two were deposited under conditions dominated by the presence of ice sheets, while the last three units reflect little or no influence of ice sheets. The regional distribution of surficial units on the Grand Banks of Newfoundland is shown in Figure 4.9.

The Grand Banks Drift is a glacial till, consisting of poorly-sorted, gravelly and sandy muds. This unit was formed directly beneath grounded ice, conformably overlies the bedrock surface and is confined to the deeper basins, channels and the saddles between offshore banks. Grand Banks Drift outcrops as a surficial unit in St. Pierre Channel, Placentia Bay, Haddock and Avalon Channels and Downing Basins northward to the Northeast Newfoundland Shelf. It has also been identified acoustically as a subsurface unit within the many buried channels on the bank tops.

bedforms. These bedforms include relict features such as shoreface-connected ridges and recent features such as sand waves and ripples, and may exhibit local areas of recently-formed gravel lags.

Finally, the Placentia Clay is a late Wisconsinan-Holocene clay derived from winnowing of the tills and glacial sediments on the bank tops during transgression of the shelf. These sediments occur in the basinal areas of the shelf and are typified by strongly to weakly laminated, sandy to silty clay, perhaps with a significant ice-rafted component of coarse materials. Placentia Clay is found primarily within Downing Basin and Placentia Bay and probably represents deposition in a relatively quiescent environment.

Figure 4.9 shows the regional surficial distribution of these five sedimentary units over the Grand Banks of Newfoundland. However, it should be realized that localized variations in surficial sediment type are common, and are generally unmapped for much of the Grand Banks. Detailed mapping of the Hibernia area has been done by Edward L. King and Associates (1989); a reduced version of their Hibernia surficial geology map is provided as Figure 4.10. A comparison between Figures 4.9 and 4.10 shows the importance of detailed mapping exercises in determining site-specific seabed characteristics and the scale of local variability in surficial geology. The scale of observed seabed variability is strongly related to the scale at which data are available and at which mapping is performed.

For the purposes of this project, the surficial geologic unit as mapped on a regional basis (Figure 4.9) has been included in the environmental database.

4.3.3 Seabed Features

The major surficial geologic features on the Grand Banks of Newfoundland are shown in Figure 4.11, based on a compilation completed in 1985 at the Atlantic Geoscience Centre (Cameron and Best 1985). It should be realized that much of the information presented in this figure is qualitative and speculative, since many areas of the Grand Banks seabed have not yet been surveyed in detail.

Figure 4.11 indicates a wide range of seabed features, including areas of iceberg scouring, sand ridges, sand waves, shell beds, pockmarks and seabed depressions of unknown origin. Seabed texture and gravel content are also indicated, as is a postulated position for the Late Wisconsinan low stand of sea level (at approximately 100 m water depth) and the related terrace in the Hibernia area.

Bedrock is shown outcropping at the seabed in the western and southwestern portions of Grand Bank, indicating areas where seabed ice-contact features would not be expected to form. High gravel content sediments are found in the deeper areas of Avalon Channel, reflecting the source of the sediments as glacial till and perhaps the presence of ice-rafted

4.3.4 Geotechnical Properties

It is the top few metres or tens of metres of seabed that are of particular relevance to the formation and persistence of iceberg pits. The thickness of this layer is represented by the maximum depth to which icebergs, waves and currents affect the characteristics of the seabed. Of the various geologic properties of the surficial sediments, several are expected to directly influence the formation, characteristics and longevity of iceberg pits. These include geotechnical properties such as shear strength, unconfined compressive strength, density, moisture content and grain size; thickness of any sediment layers or depth to an underlying hard layer; and some measure of the mobility of the seabed sediments as related to pit degradation and infilling. The issue of seabed mobility will be discussed in Section 4.3.5 of this report.

Unfortunately, little direct information is available to describe the spatial variability of seabed geotechnical properties on a regional basis. Instead, indirect measures must be substituted based on data availability. While site-specific geotechnical data are available in the Hibernia area (shear strength, density, etc.), no regional data are currently available to describe spatial variations in these properties. Therefore, other data which could act as indirect indicators of geotechnical parameters must be considered in the spatial analyses described in Section 6.0 of this report.

Two types of information are available for this purpose: surficial sediment grain size and surficial geologic unit. The surficial geologic units on the Grand Banks of Newfoundland have been described in Section 4.3.2; the regional distribution of these formations is shown in Figure 4.9. The geologic unit may, as an indication of geologic history, reflect to some degree variations in geotechnical properties of the seabed (e.g. sediment density, level of consolidation, etc.).

Regional variations in grain size characteristics of the surficial sediments have been obtained from the database of grab and core samples maintained at the Atlantic Geoscience Centre (G. Sonnichsen, pers. comm.). This database includes roughly 690 samples within the study area. Mean grain size, standard deviation, and gravel, sand, silt and clay contents as weight percents were available for each sample. The locations of samples from this database are shown in Figure 4.13, with the resulting regional map of mean grain size of the surficial sediments shown in Figure 4.14. Mapping procedures are discussed in Section 5.0 of this report.

4.3.5 Seabed Mobility

The degree of seabed sediment mobility may have several important impacts on the persistence and characteristics of ice-contact features on the seabed. Firstly, in areas with relatively-mobile seabed sediments or high siltation rates, any seabed depressions such as iceberg pits or furrows may be rapidly erased from the seabed record or appear only as

The sediment mobility indices have been calculated for each unique combination of input parameters. The first index, representing the net sediment transport rate, has been calculated using methods described by Davidson (1991). Spatial variations over the Grand Banks of Newfoundland are shown in Figure 4.15. The second mobility index represents the ratio of actual seabed shear stress, under the above conditions, to the critical stress level required for the initiation of bedload transport; spatial variations are shown in Figure 4.16. This second index may more accurately represent the effects of seabed reworking in wave-dominated environments, when sediment movement tends to be oscillatory, with considerable sediment in motion but very low net transport rates.

Due to the limitations and assumptions inherent in the input data described above and uncertainties in the appropriate methods for calculation of seabed stresses and sediment transport rates, these parameters should be considered as qualitative indices rather than as quantitative values. Although the order of magnitude of the transport rates might not be correct, it is believed that the results presented in Figures 4.15 and 4.16 give a reasonable picture of the spatial variations in both sediment transport rate and seabed mobility over the study area.

4.4 Iceberg Characteristics

The frequency of iceberg grounding events and the physical dimensions of grounding icebergs are important factors influencing the frequency of formation and characteristics of iceberg pits on the Grand Banks of Newfoundland. Measurements of iceberg dimensions, particularly draft, are extremely limited and are not available on a regional basis. Available measurements are summarized by Hotzel and Miller (1983), Ice Engineering Ltd. (1983), Hodgson et al. (1988), Clark et al. (1990) and others.

The frequency of formation of iceberg pits on the Grand Banks of Newfoundland is likely to be strongly linked to the frequency of iceberg grounding events. However, regional data describing iceberg grounding events were not available for this project. Instead, estimates of the probability of occurrence of icebergs over the study area have been used in the environmental factor database. Since iceberg grounding occurs when the draft of an iceberg exceeds the local water depth, the frequency of grounding events is linked to iceberg occurrence through the distribution of iceberg drafts at each location of interest.

Icebergs found on the Grand Banks of Newfoundland have their origins primarily on the west coast of Greenland, where they are calved from tidewater glaciers. The prevailing ocean currents shown in Figure 4.3 transport icebergs northwards and southwards, with roughly 400 icebergs per year drifting south of 48°N onto the Grand Banks (Ebbesmeyer et al. 1980). The average annual flux of icebergs onto the banks is highly variable, ranging from zero to over 2000 (Lewis and Woodworth-Lynas 1990).

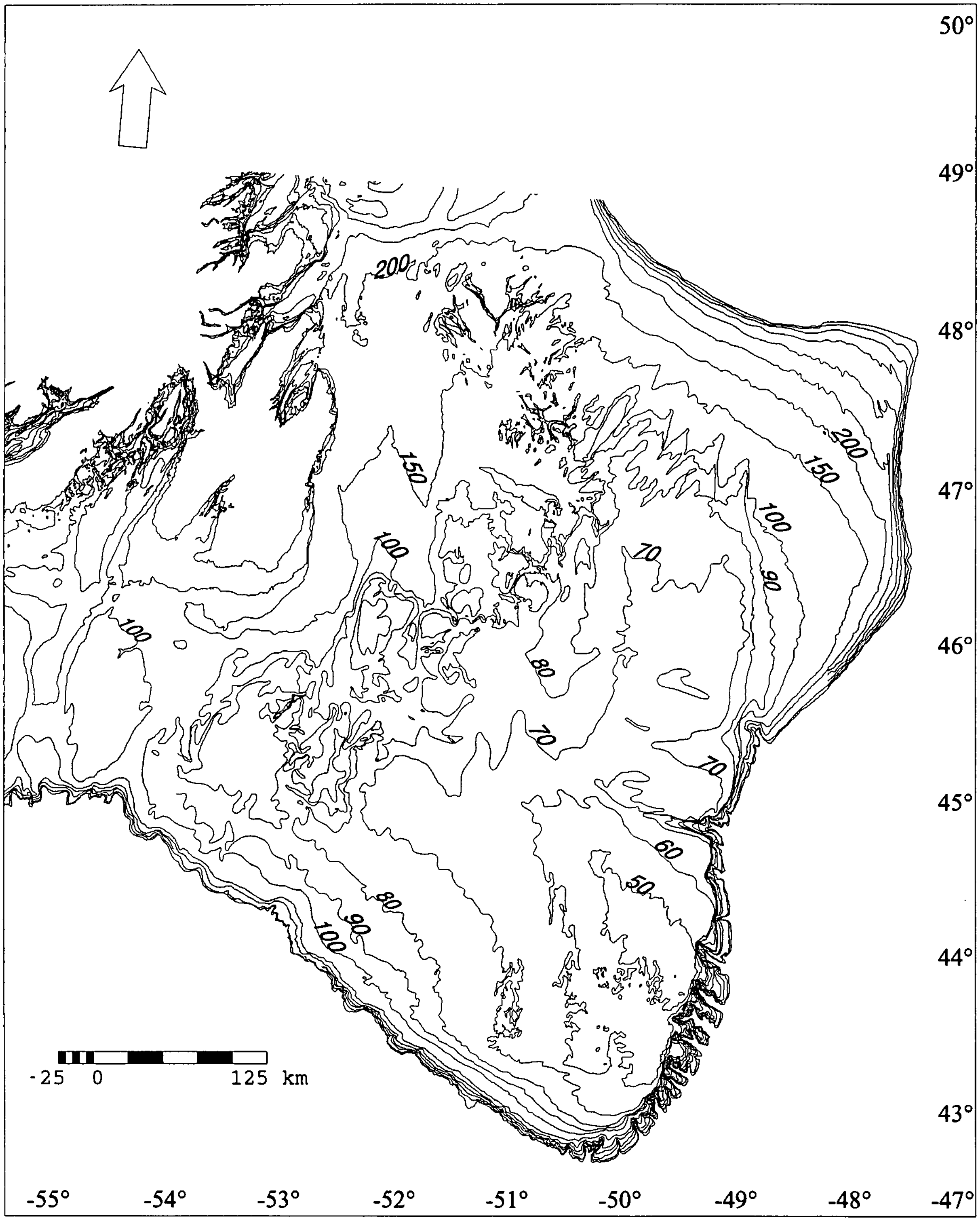


Figure 4.1 Bathymetric contours for the Grand Banks of Newfoundland.

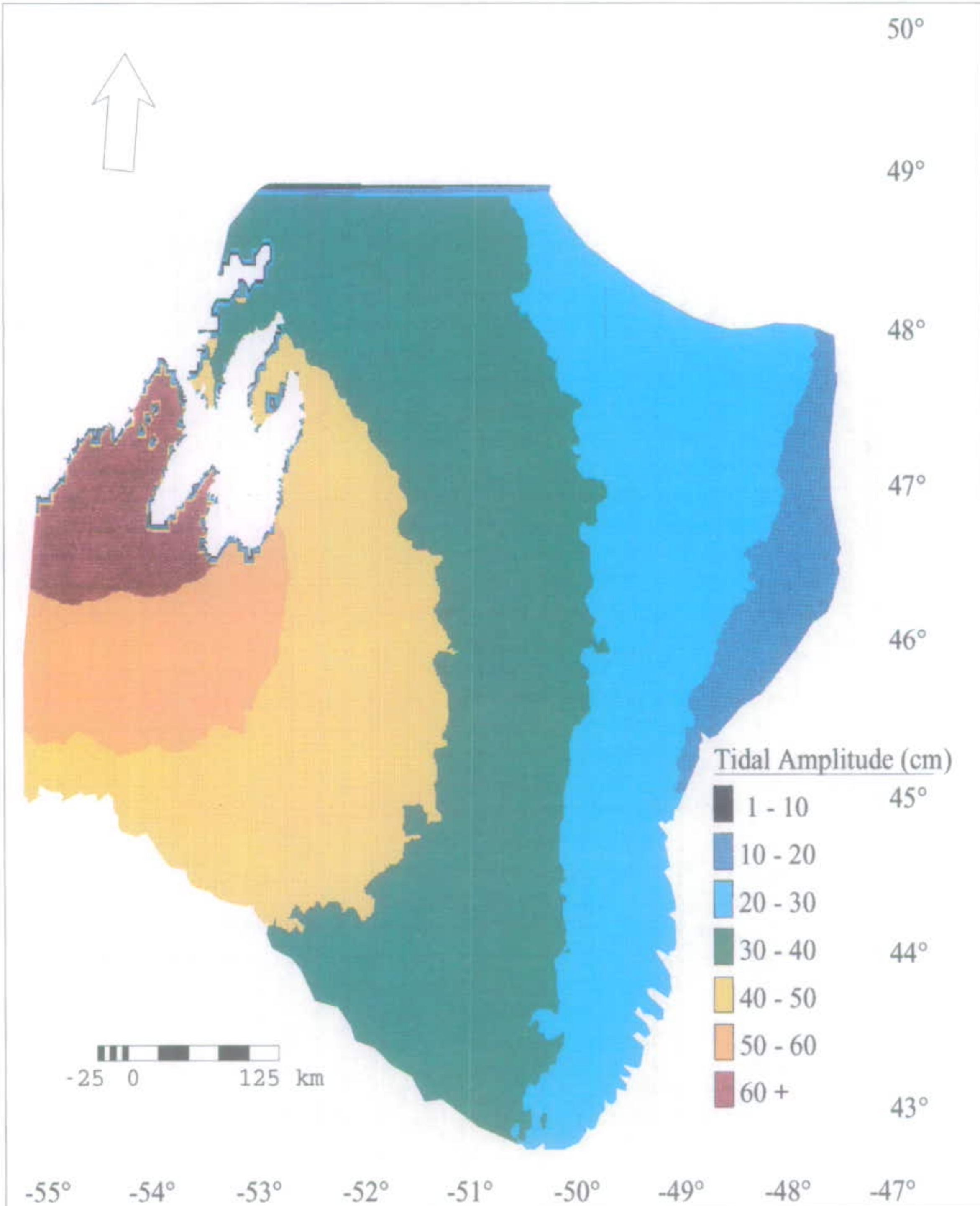


Figure 4.2 **Maximum amplitude of tidally-induced water level fluctuations over the study area (approximated by sum of M_2, K_1 and O_1 amplitudes).**

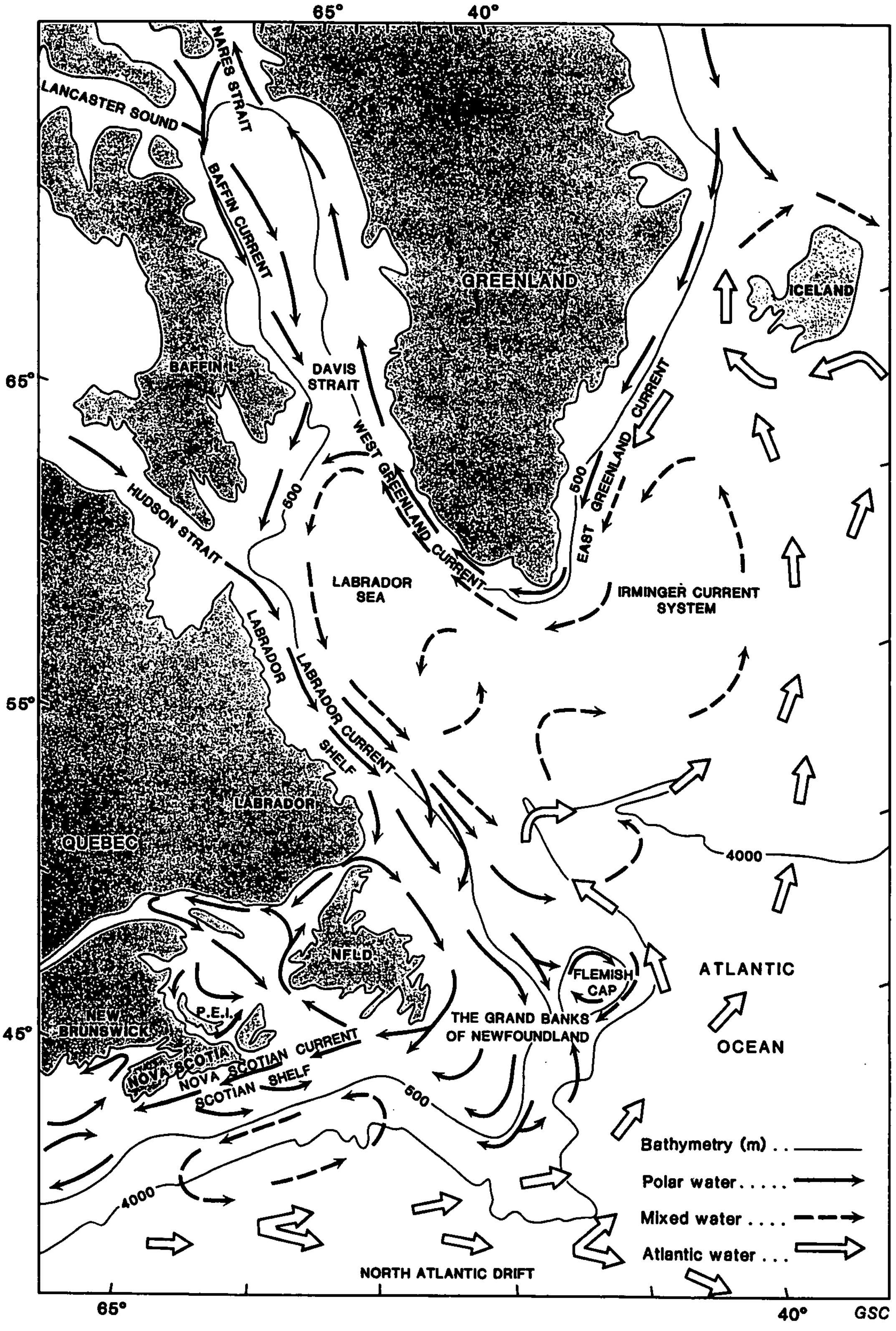


Figure 4.3. **Surface water movements in the northwestern Atlantic region (from Piper et al. 1990).**

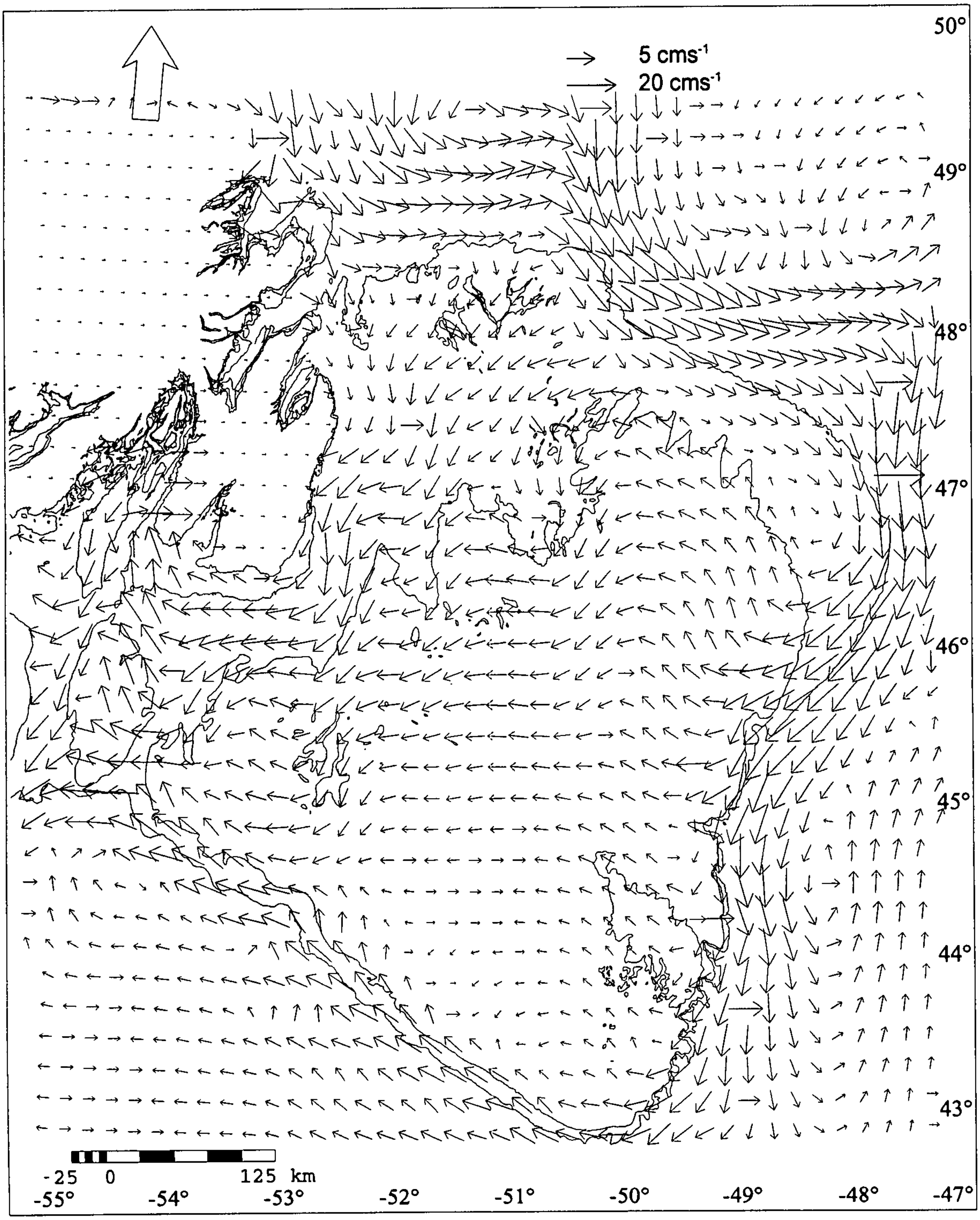
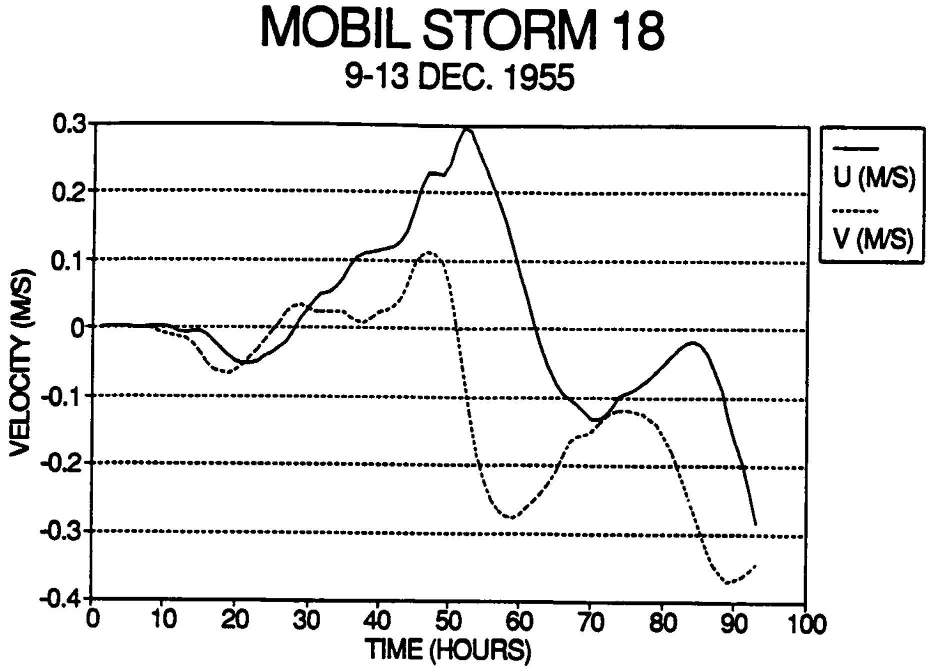


Figure 4.4 **Depth-averaged, mean current patterns on the Grand Banks of Newfoundland.**



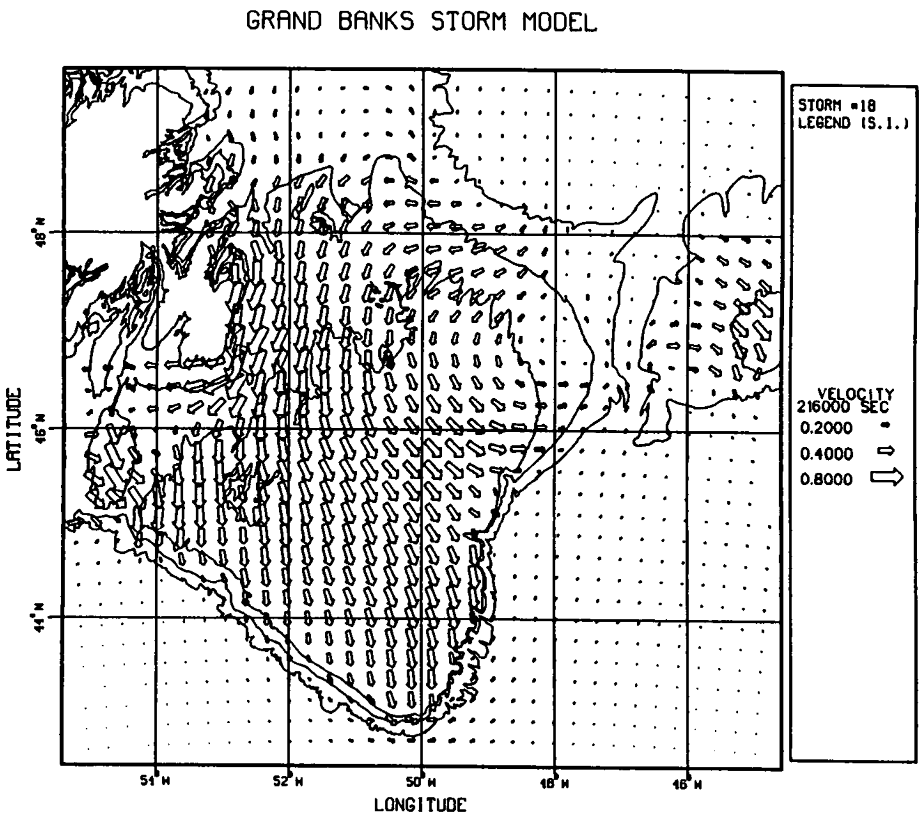


Figure 4.5 Depth-averaged, storm-driven currents on the Grand Banks of Newfoundland. Top: U (east) and V (north) components of current at Hibernia for the duration of the storm. Bottom: predicted currents at the height of the storm (from Petrie 1993).

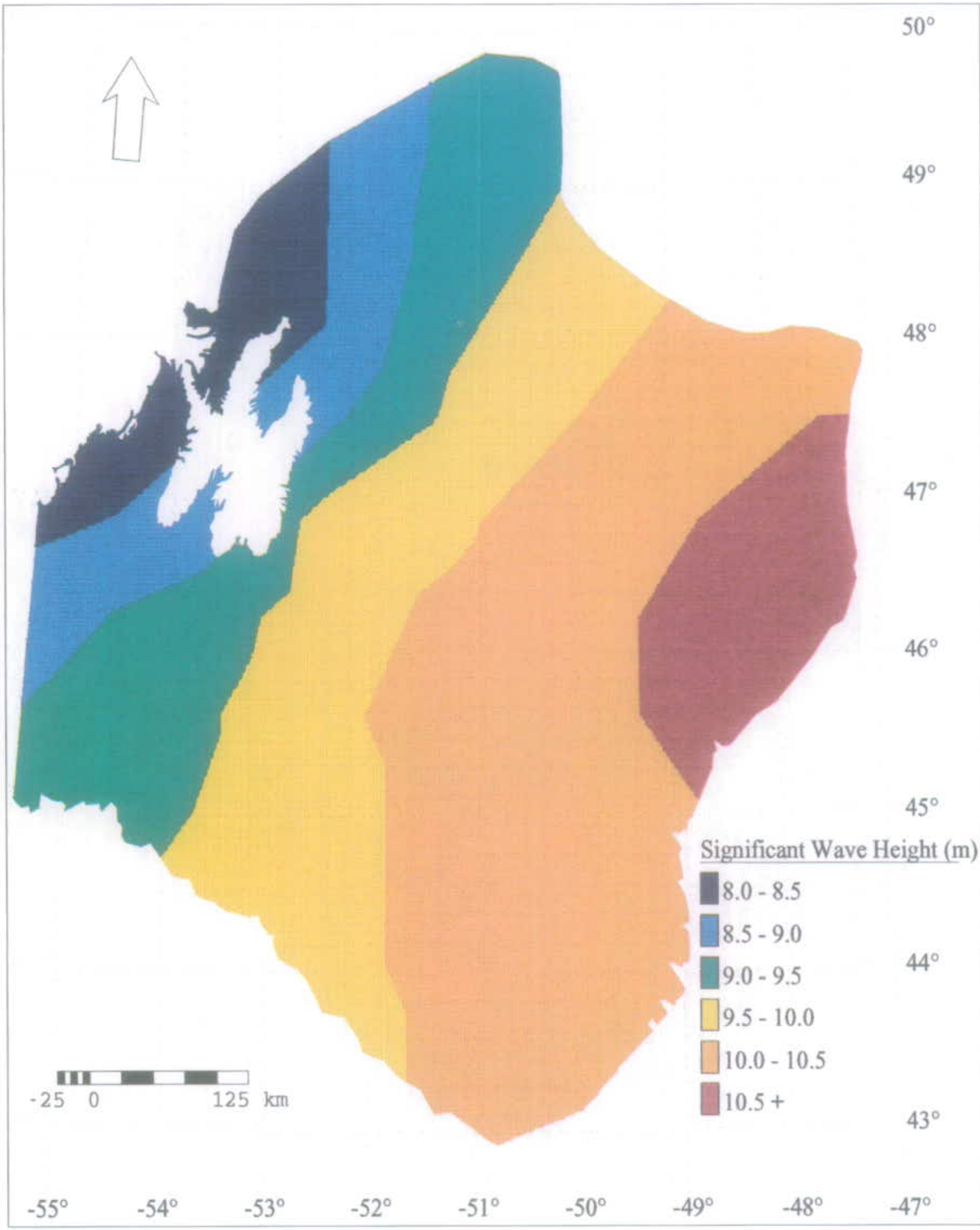
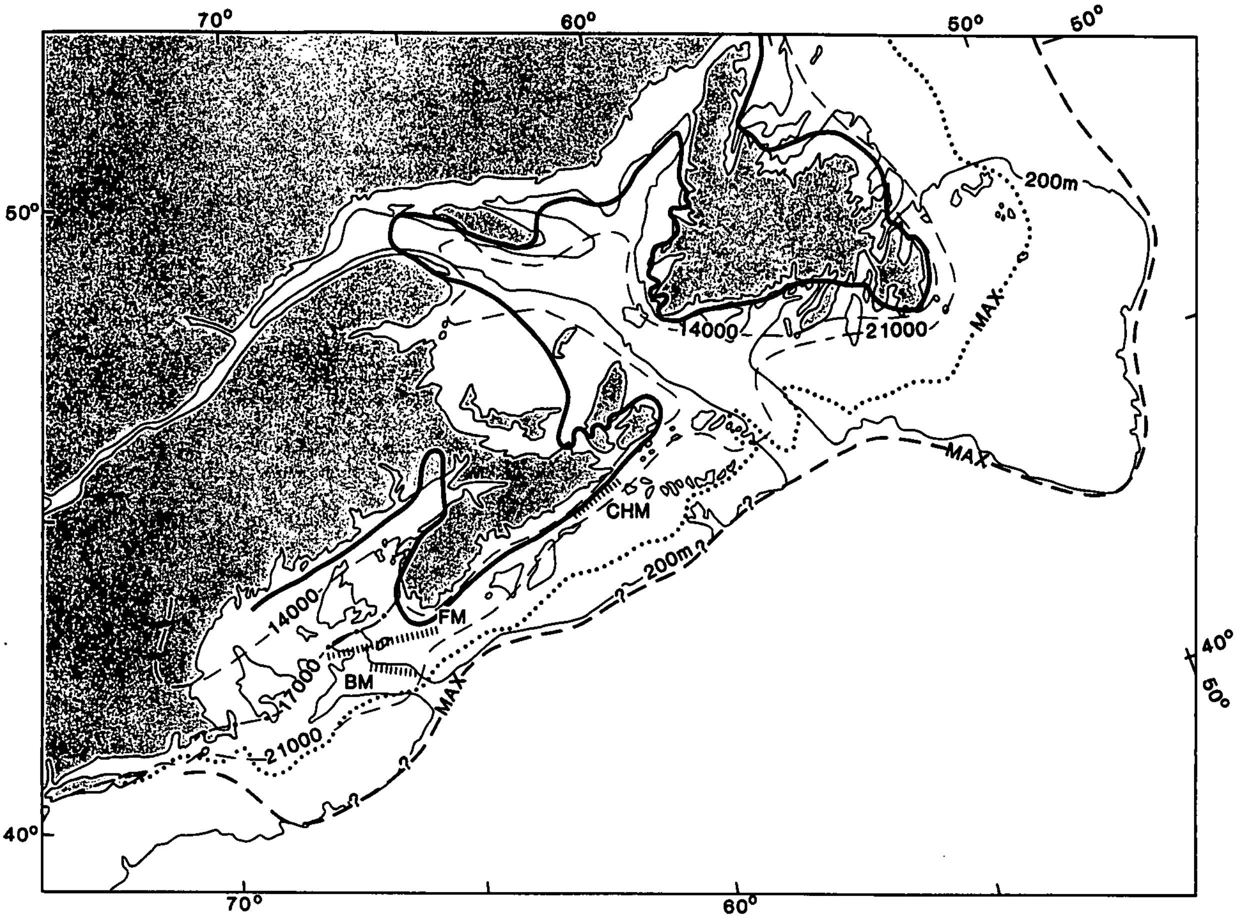


Figure 4.6 **Two-year return period significant wave heights on the Grand Banks of Newfoundland.**



||||||||| Moraine

BM Browns Moraine

CHM Country Harbour Moraine

FM Fundian Moraine

— — 14ka } Late Wisconsinan retreat positions (Denton and Hughes, 1981)
— — 21ka

······· MAX All time till limit (Prest, 1984)

——— Late Wisconsinan terrestrial limit (Grant, in press)

—•— 17ka Limit in Gulf of Maine (this paper)

— — MAX All time till limit (this paper)

GSC

Figure 4.7. **Various estimates of the maximum extent of glaciation on the east coast during the Wisconsinan period. See Piper et al. (1990 - "this paper") for references.**

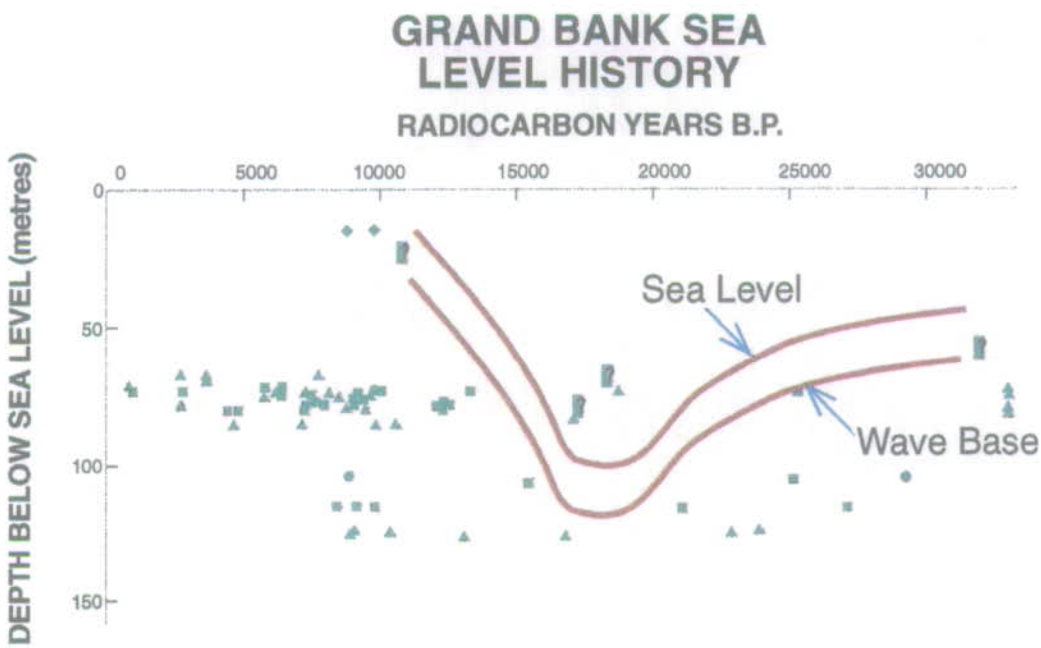


Figure 4.8 **Proposed sea level history for northeastern Grand Bank, based on the age and water depth of shells (mostly detrital mollusc and barnacle shell fragments in vibrocores from thin bedforms and sand deposits). A lowstand of sea level at approximately -100 m with a wave base at -120 m is suggested at about 18 000 years BP based on the absence of shells dating from the interval 22 000 to 14 000 BP. The four deepest shell ages at -125 m constitute a lower bound for the lowstand; they are in proper stratigraphic order in the same core, suggesting they were unaffected by the wave base of the 18 ka lowstand. The two samples above the curve were ignored as they are from mixed shell fragments and likely represent the average age of two shell populations, one > 22 000 and another < 14 000 BP (figure courtesy of the Atlantic Geoscience Centre).**

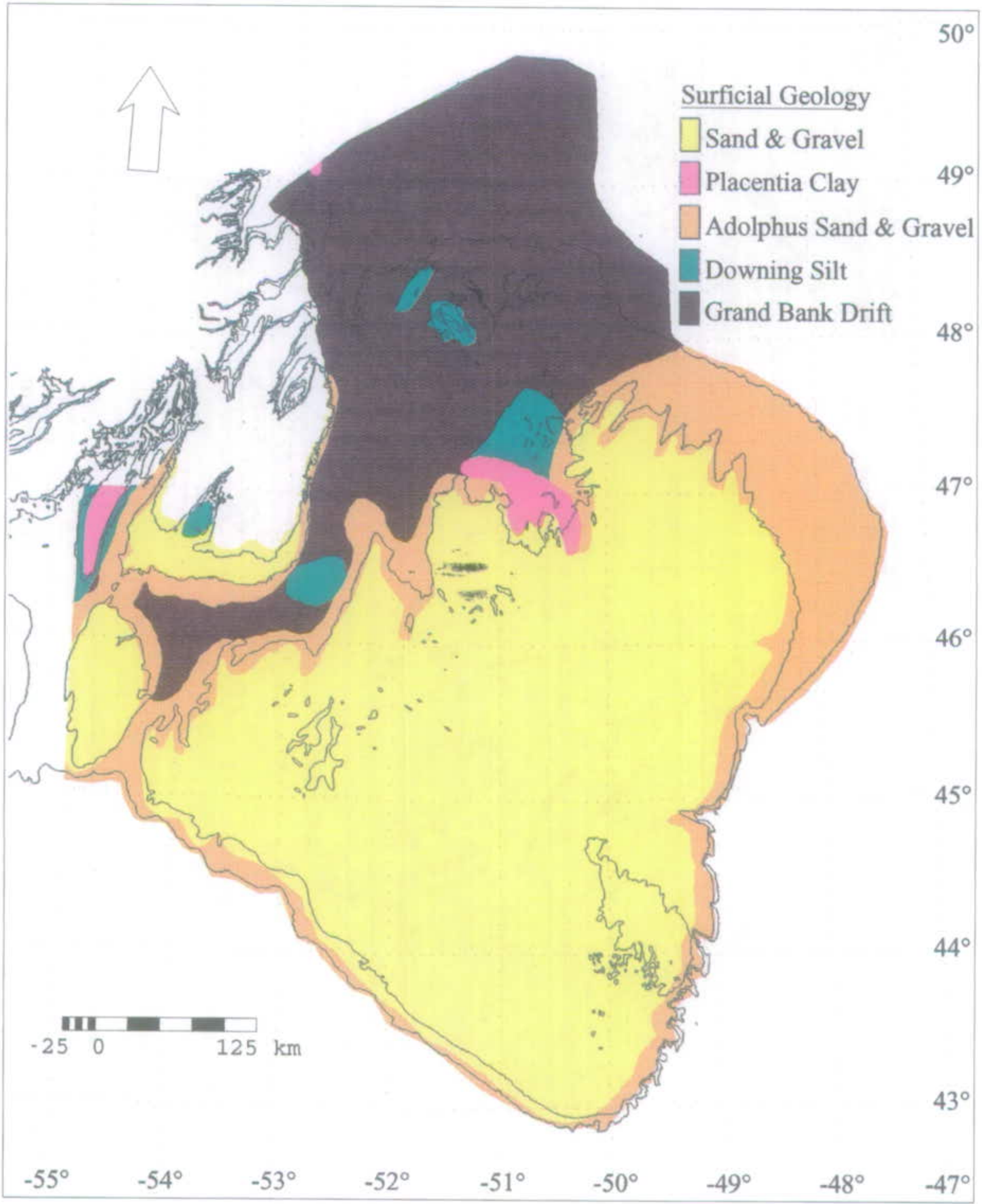


Figure 4.9 **Surficial geologic units on the Grand Banks of Newfoundland.**

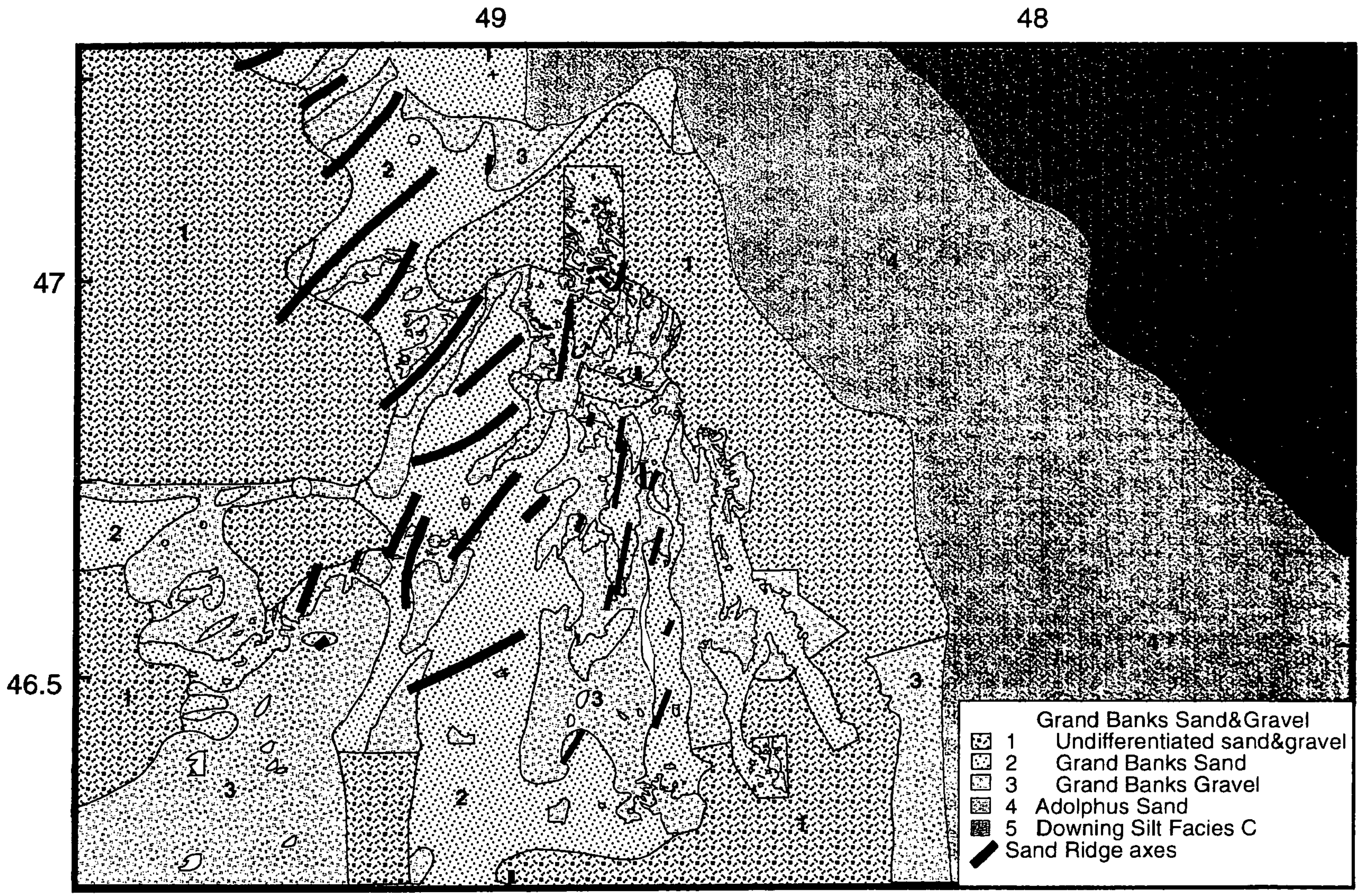


Figure 4.10 Surficial geologic units in the Hibernia region.

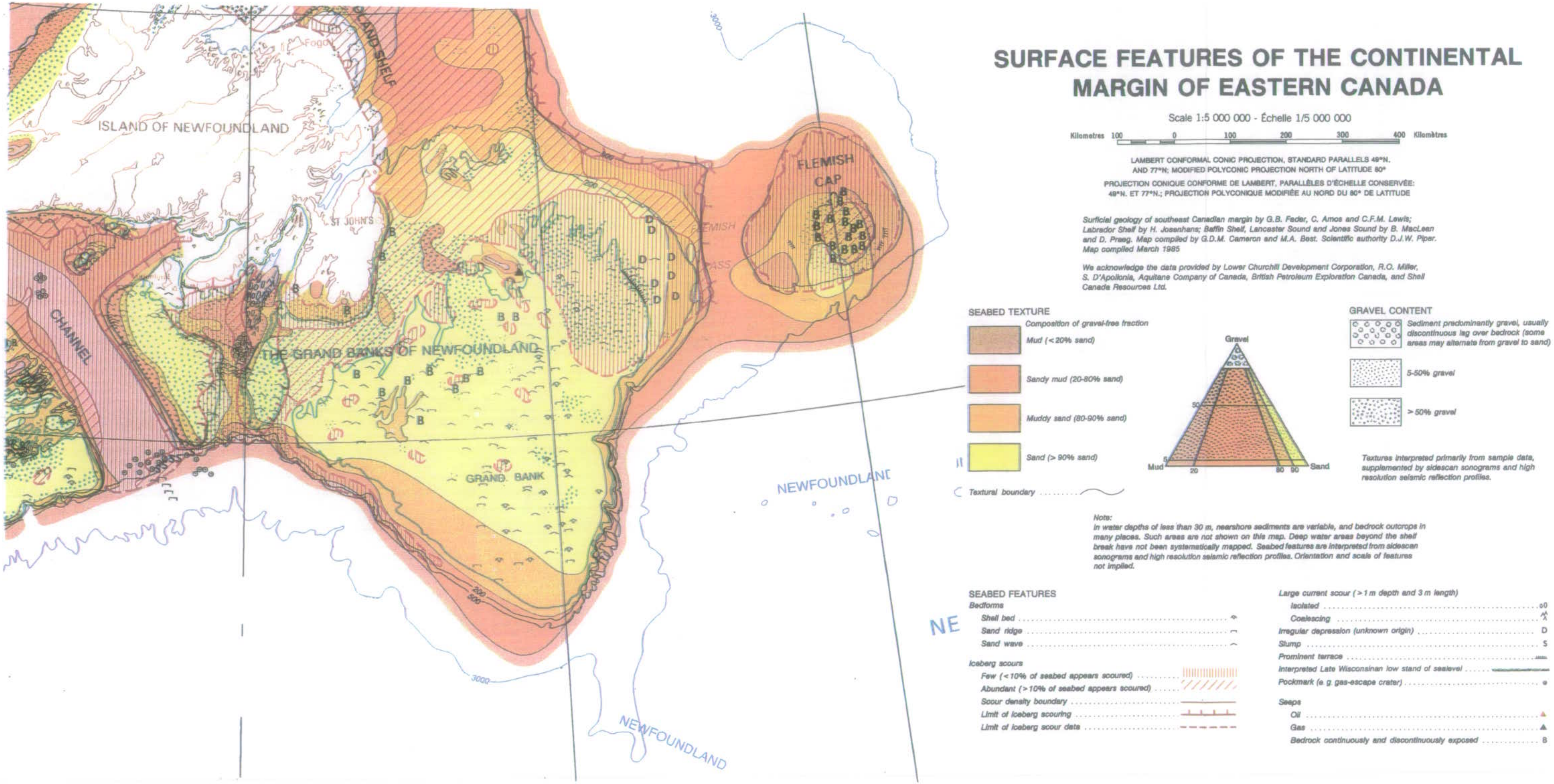
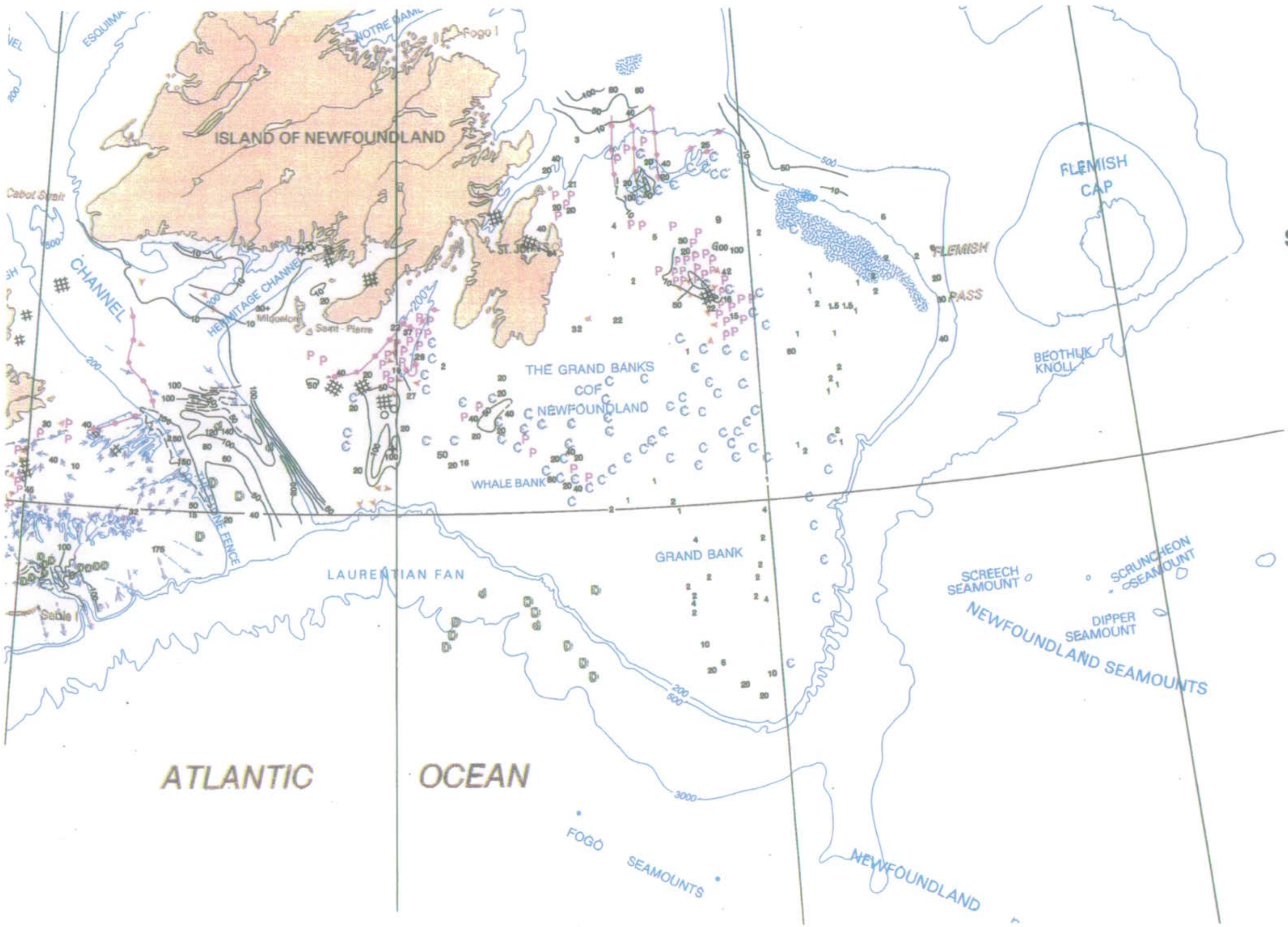

SURFACE FEATURES OF THE CONTINENTAL MARGIN OF EASTERN CANADA
Scale 1:5 000 000 - Échelle 1/5 000 000
Kilometres 100 0 100 200 300 400 Kilomètres
LAMBERT CONFORMAL CONIC PROJECTION, STANDARD PARALLELS 49°N. AND 77°N; MODIFIED POLYCONIC PROJECTION NORTH OF LATITUDE 80°
PROJECTION CONIQUE CONFORME DE LAMBERT, PARALLÈLES D'ÉCHELLE CONSERVÉE: 49°N. ET 77°N.; PROJECTION POLYCONIQUE MODIFIÉE AU NORD DU 80° DE LATITUDE
Surficial geology of southeast Canadian margin by G.B. Fader, C. Amos and C.F.M. Lewis; Labrador Shelf by H. Josenhans; Baffin Shelf, Lancaster Sound and Jones Sound by B. MacLean and D. Praeg. Map compiled by G.D.M. Cameron and M.A. Best. Scientific authority D.J.W. Piper. Map compiled March 1985
We acknowledge the data provided by Lower Churchill Development Corporation, R.O. Miller, S. D'Apollonia, Aquitane Company of Canada, British Petroleum Exploration Canada, and Shell Canada Resources Ltd.
SEABED TEXTURE
Composition of gravel-free fraction
Mud (< 20% sand)
Sandy mud (20-80% sand)
Muddy sand (80-90% sand)
Sand (> 90% sand)
Textural boundary
Gravel
Mud
Sand
50
5
20
80
90
GRAVEL CONTENT
Sediment predominantly gravel, usually discontinuous lag over bedrock (some areas may alternate from gravel to sand)
5-50% gravel
> 50% gravel
Textures interpreted primarily from sample data, supplemented by sidescan sonograms and high resolution seismic reflection profiles.
Note:
In water depths of less than 30 m, nearshore sediments are variable, and bedrock outcrops in many places. Such areas are not shown on this map. Deep water areas beyond the shelf break have not been systematically mapped. Seabed features are interpreted from sidescan sonograms and high resolution seismic reflection profiles. Orientation and scale of features not implied.
SEABED FEATURES
Bedforms
Shell bed
Sand ridge
Sand wave
Iceberg scours
Few (< 10% of seabed appears scoured)
Abundant (> 10% of seabed appears scoured)
Scour density boundary
Limit of iceberg scouring
Limit of iceberg scour data
Large current scour (> 1 m depth and 3 m length)
Isolated
Coalescing
Irregular depression (unknown origin) D
Slump S
Prominent terrace
Interpreted Late Wisconsinan low stand of sealevel
Pockmark (e.g. gas-escape crater)
Seeps
Oil
Gas
Bedrock continuously and discontinuously exposed B
ISLAND OF NEWFOUNDLAND
ST JOHN'S
THE GRAND BANKS OF NEWFOUNDLAND
GRAND BANK
FLEMISH CAP
FLEMISH PASS
CHANNEL
NEWFOUNDLAND
3000
200
500

Figure 4.11



SUBSURFACE QUATERNARY FEATURES OF THE CONTINENTAL MARGIN OF EASTERN CANADA

Scale 1:5 000 000 - Échelle 1/5 000 000

Kilometres 100 0 100 200 300 400 Kilomètres

LAMBERT CONFORMAL CONIC PROJECTION, STANDARD PARALLELS 49°N. AND 77°N; MODIFIED POLYCONIC PROJECTION NORTH OF LATITUDE 80°

PROJECTION CONIQUE CONFORME DE LAMBERT, PARALLÈLES D'ÉCHELLE CONSERVÉE: 49°N. ET 77°N.; PROJECTION POLYCONIQUE MODIFIÉE AU NORD DU 80° DE LATITUDE

SUBSURFACE QUATERNARY FEATURES

Isopach (total thickness)

- *Quaternary, 10, 50, 100 and 200 metre contours, defined, approximate*
- *Spot thickness in metres*

Features

- *Regional morainal ridge (large moraine complex, up to 150 metres thick, interpreted to form near a grounding line of an ice shelf)*
- *Parallel till ridge (mound-like linear ridges of till, 5-20 metres thick, interpreted as "lift off moraines" beneath ice shelves)* — P
- *Till tongue*
- *Diapir* — D
- *Diapir-like structure* — d
- *Channel defined, approximate (direction of flow indicated by arrow)*
- *Zone of abundant channelling* — C
- *Buried pockmark* — o
- *Buried iceberg scour*
- *Gas charged sediment* — #
- *Location of 1929 earthquake of magnitude 7.2* — +

Figure 4.12

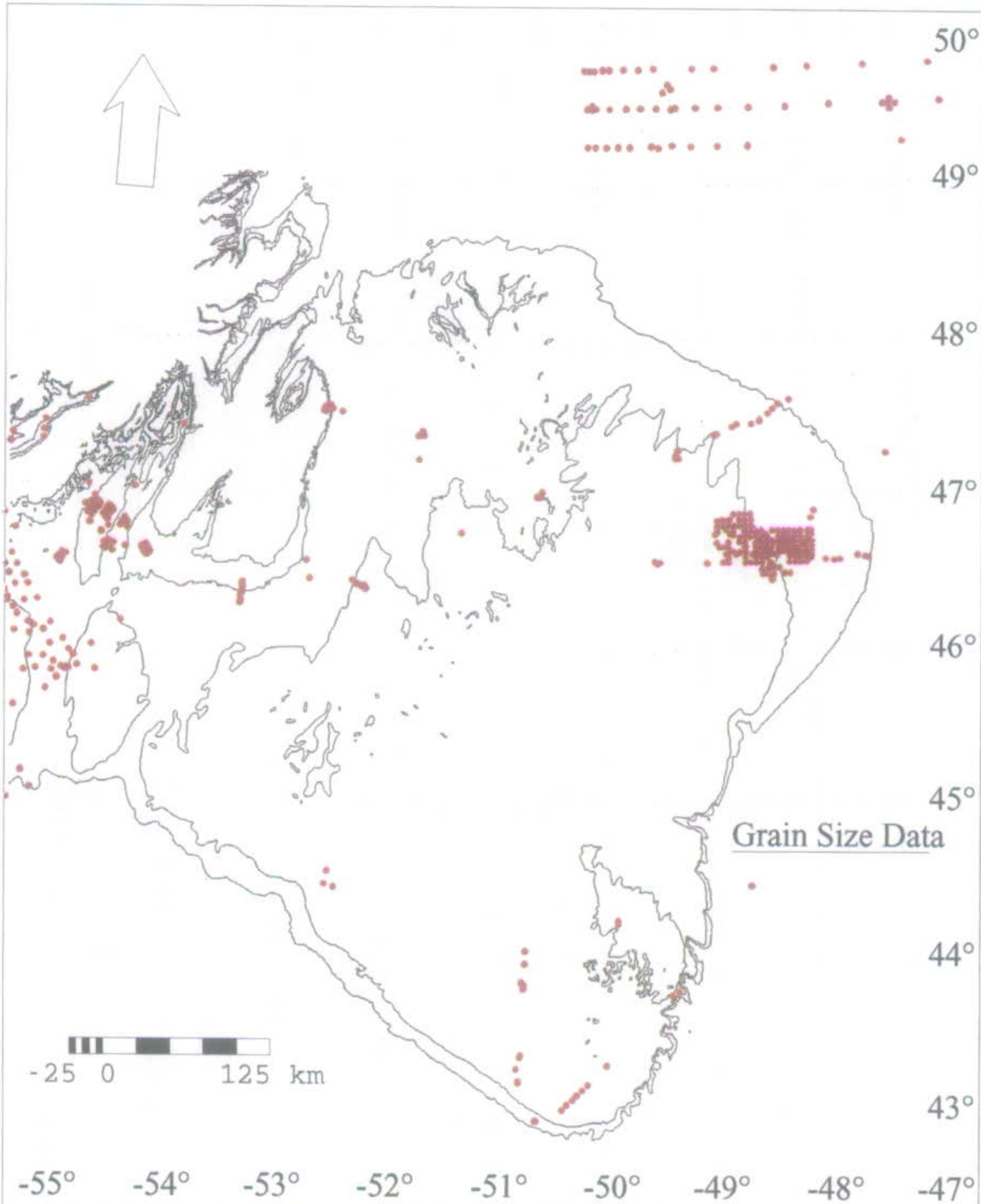


Figure 4.13 Sample locations for AGC database of surficial sediment samples.

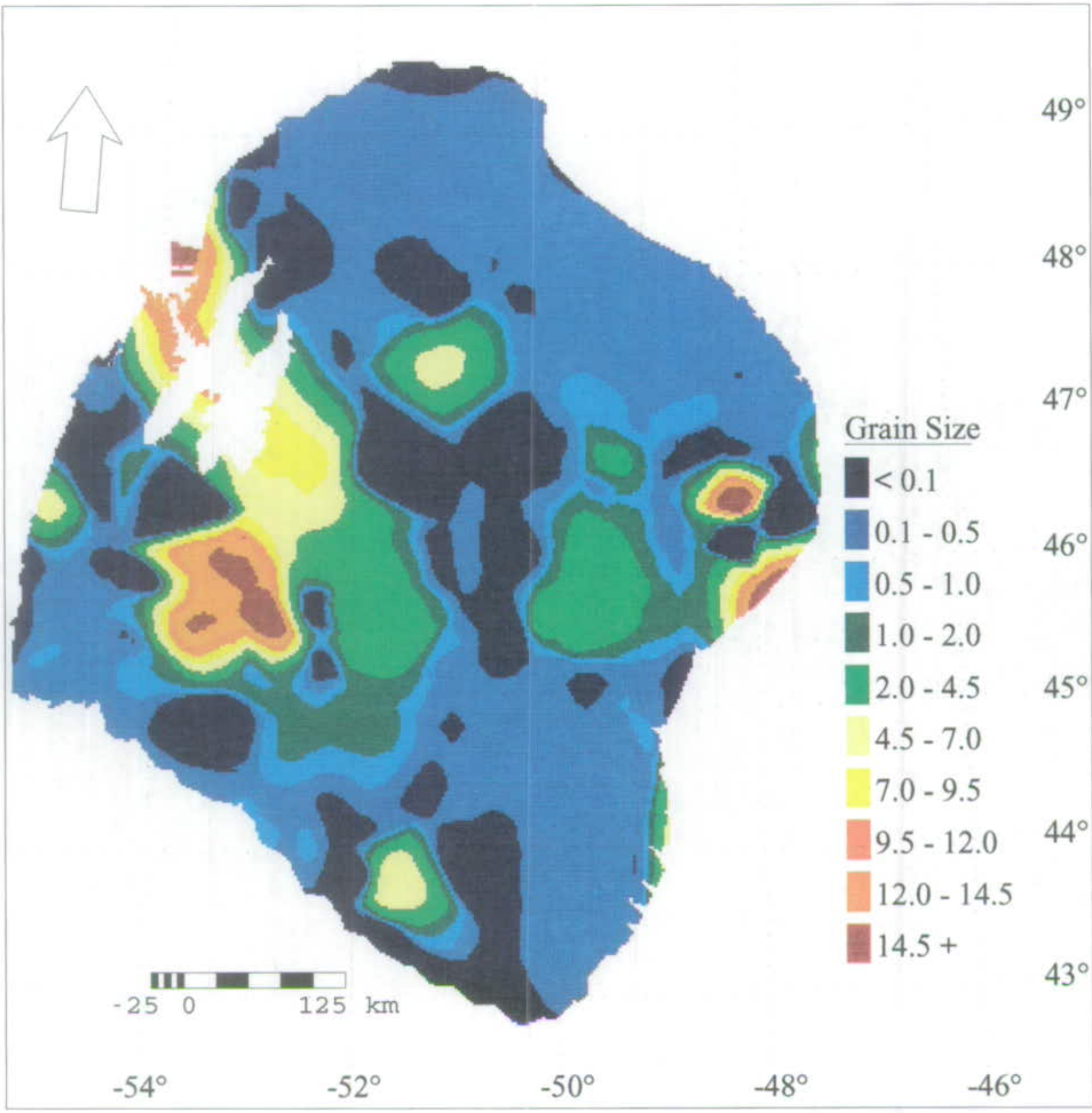


Figure 4.14 Regional variations in mean grain size (mm) of surficial sediments on the Grand Banks of Newfoundland.

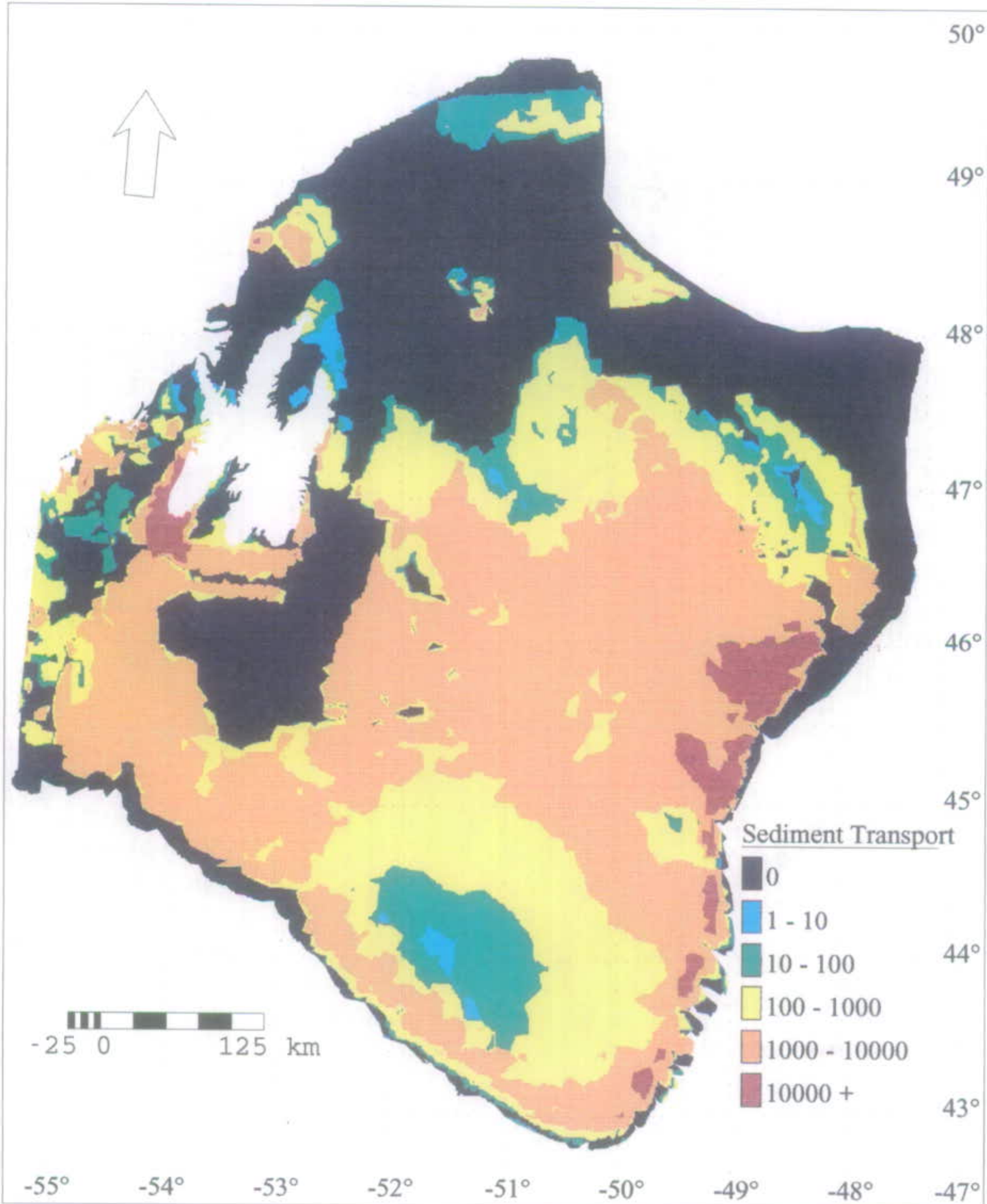


Figure 4.15 **Spatial variations in net rate of sediment transport (kg m^{-1} s^{-1}, multiplied by 10^6) over the Grand Banks of Newfoundland.**

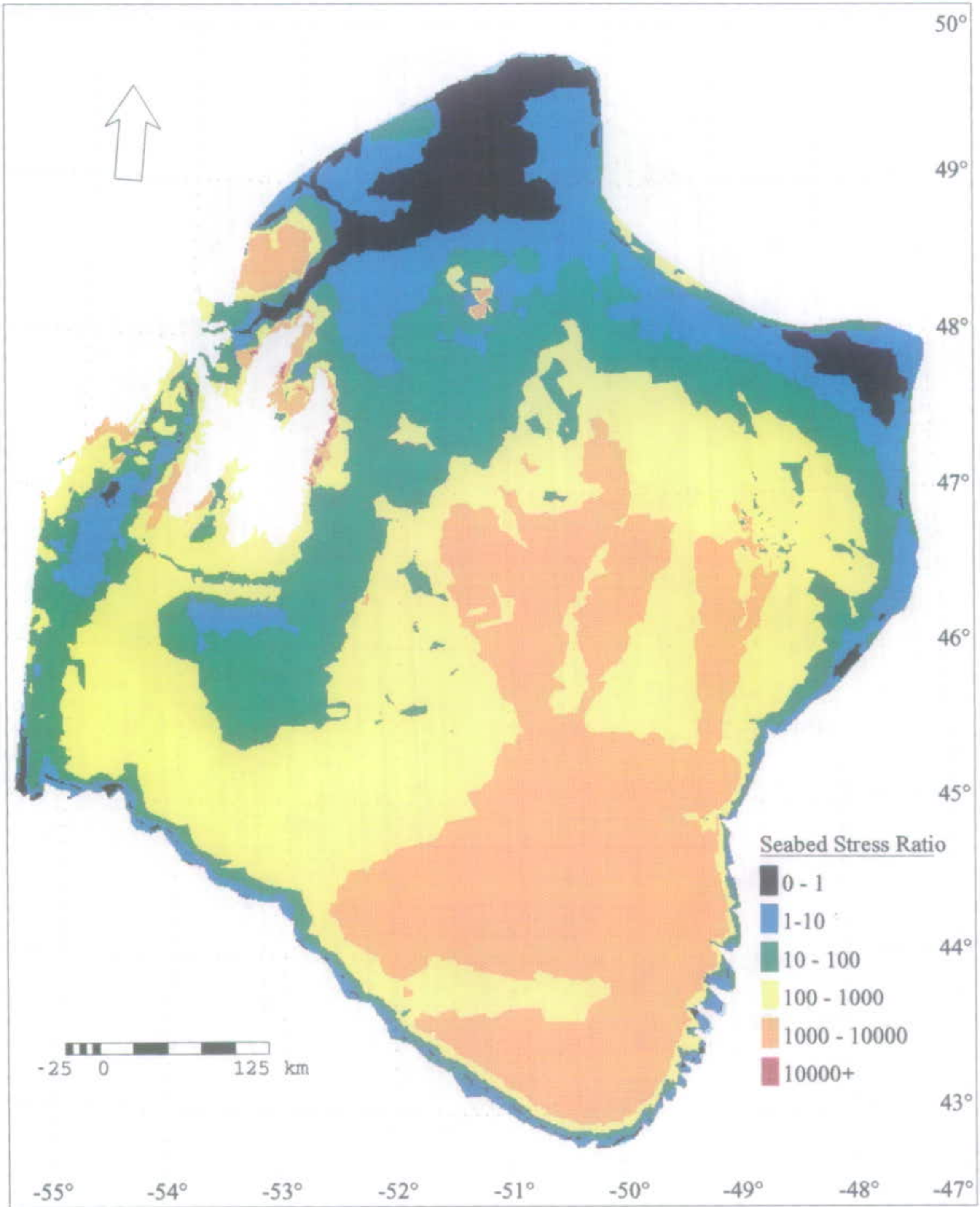


Figure 4.16 **Spatial variations in the ratio of seabed stress (calculated using the two-year return period wave conditions) to the critical stress required for initiation of bedload transport (multiplied by 100).**

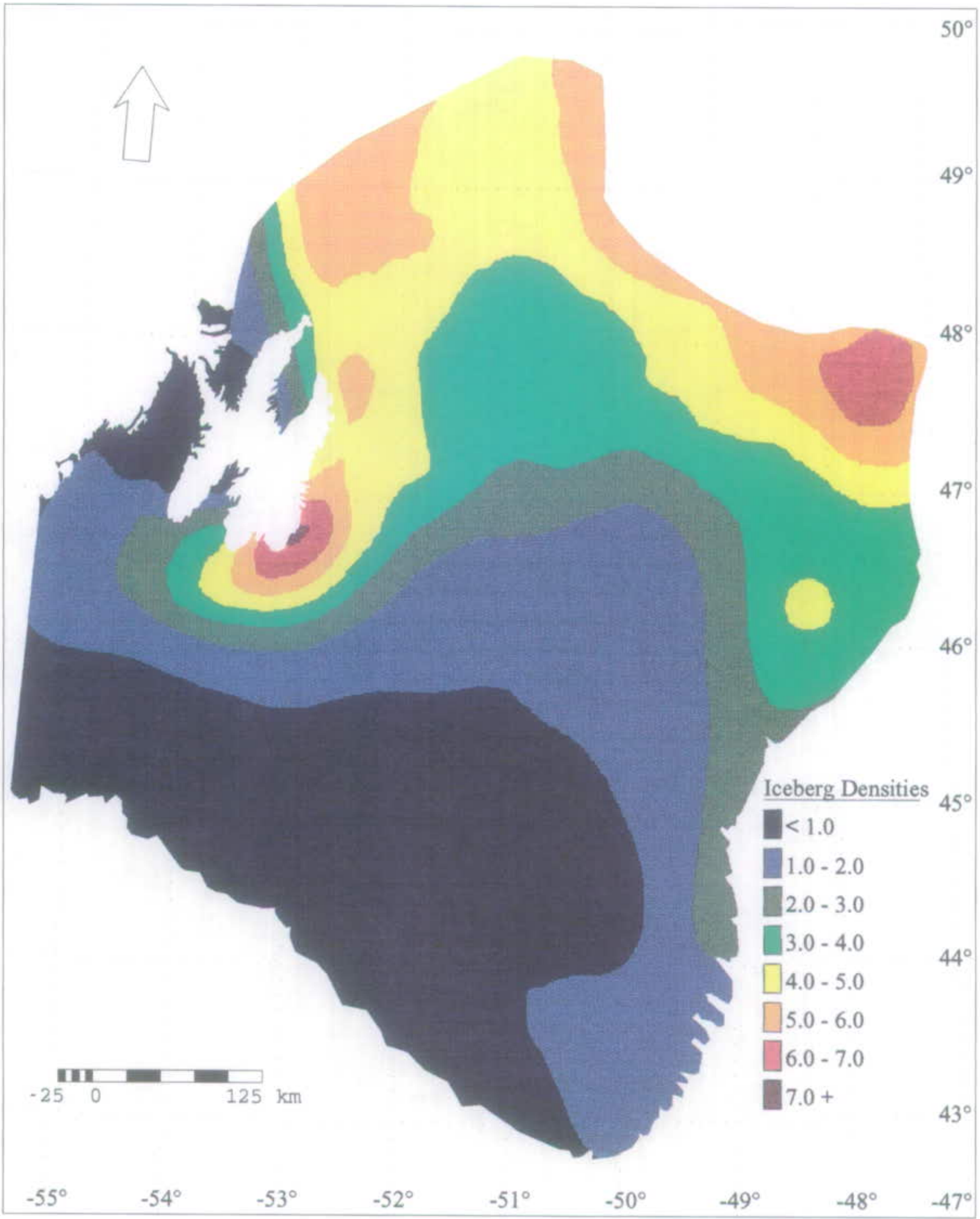


Figure 4.17 **Average annual iceberg densities on the Grand Banks of Newfoundland (bergs per 100 km^2 per year, multiplied by 100). Observations have been corrected for search area and number of overflights.**

5. THE ICEBERG PIT GEOGRAPHIC INFORMATION SYSTEM

5.1 Development of the Iceberg Pit GIS

As described in Section 4.0 of this report, many of the environmental data used in this project were obtained in point form. Point data usually contain location parameters such as latitude and longitude or x,y coordinate pairs (e.g., UTM projection coordinates), together with a non-spatial attribute such as wave height, tidal amplitude or sediment grain size. Point data may be regularly spaced, as for the tide, wave, iceberg and current data sets (Sections 4.2 and 4.4), or irregularly spaced, such as the surficial grain size information or the sediment mobility parameters (Section 4.3).

For this project, iceberg pit features have also been represented as point data. Pit features are relatively small, particularly when compared with the spatial scales associated with the regional variability in the environmental parameters. Thus, it is not expected that environmental parameter values will change significantly over the area covered by a single iceberg crater. While small-scale variability certainly does exist (e.g., compare Figures 4.9 and 4.10), the present study focuses on regional trends rather than on the effects of local variability.

In order to analyse the various environmental parameters in a geographic information system (GIS) and to include regions with no data in the analysis process, the point measurements must first be extended to cover the entire study area. The techniques used to convert the point data to regional maps can be divided into continuous and discrete interpolation methods. Both continuous and discrete interpolation techniques are based on the concept of positive spatial auto-correlation, whereby, on average, points that are close together geographically are more likely to have similar data values.

A basic assumption of continuous interpolation methods is that the data values change gradually throughout the study area. In addition, continuous interpolation algorithms are appropriate only for point data that are well-distributed throughout the study region. For this project, the Delaunay Triangulated Irregular Network (TIN) algorithm has been used to create continuous surfaces for the wave height, tidal amplitude, current speed, and iceberg density data sets. All of these data sets represent the results of various numerical models, where model computations were performed at a set of regularly-spaced grid points. The TIN approach was also used to map the sediment mobility indices; although data points were not based on a regular-grid, they were well-distributed throughout the study area.

The TIN algorithm preserves the values at the data points as well as the high and low areas throughout the study area. This algorithm is appropriate for data where local or regional trends are easily detected. A TIN algorithm constructs a surface by deriving a set of interconnected triangular facets from the distribution of the point data; intermediate values at locations between the data points are then determined by linear interpolation along the facet face.

An example of continuous interpolation using the TIN algorithm is given in Figure 5.1. This figure shows the locations of the points for which wave height data were available, together with the actual data values for the two-year return period wave heights. Also shown are the contour lines generated by the TIN algorithm. The contour lines 'pass through' the wave height data points and are assigned the values of these points. This map can be used for modelling or can be classified to produce a generalized map of spatial variations in wave height (Figure 4.6).

For this project, the Triangulated Irregular Network or TIN algorithm in the SPANS GIS software package has been used to map point data such as wave period, wave height and iceberg density. The TIN algorithm in SPANS provides the user with the option of selecting a linear- or polynomial-based contouring method. It should be noted that the linear function honours or preserves the data points, while the polynomial produces a smoother and more generalized surface. The linear option has been used in this study. TIN algorithms are only appropriate for spatial data that exhibit trends similar to that of the wave height data.

If the distribution of point data is sparse or if the non-spatial attribute is a nominal value (e.g., surficial geologic unit), a discrete interpolator is a more appropriate method for creating maps. The discrete interpolation technique used in this study is the Thiessen or Voronoi polygon method. This method divides the region into polygons, where each polygon has the same attribute value. Polygon shape is determined by the spatial distribution of the data points. In areas with many data points, polygons are small, while polygons are large where data coverage is sparse. If the data points lie on a regularly-spaced square grid (e.g., Figure 5.2), the Voronoi polygons become uniform squares with the dimension equal to the grid spacing. Thus, point data based on a 1 x 1 km grid would produce a map consisting of 1 km^2 polygons (Figure 5.3). Irregularly spaced data will produce a series of irregular polygons.

The Voronoi algorithm was used to map the sediment grain size point data for this project. However, the procedure was different than the preceding method in that the Voronoi polygons were based on the actual distribution of the data points (Figure 4.13). The resulting polygons are irregular in shape and their size is based on the density of the data points. For example, the Voronoi routine will create larger polygons for sparse point distributions and smaller polygons for densely-clustered point patterns. This is due to the fact that a Voronoi polygon boundary is formed by drawing lines half-way between a point and each of its nearest neighbours. The Voronoi polygons resulting from the point distribution for the surficial sediment data are shown in Figure 5.4, with the associated map of sediment grain sizes presented as Figure 5.5.

A comparison of Figure 5.5 with Figure 4.14 illustrates, in a qualitative sense, the differences between maps developed using the Voronoi polygon method and a TIN approach. The map presented in Figure 4.14 was actually created using a modified TIN approach, where an artificial, regularly-spaced data set was created by sub-sampling the Voronoi grain size map (Figure 5.5). This regularly-spaced data set was then used to create the TIN map shown as Figure 4.14. Without this intermediate step, the TIN algorithm would have failed due to the sparse and irregularly-spaced nature of the original grain size data. For this project, the Voronoi map was used for analysis purposes since it preserves the values at the original data points.

Voronoi polygons can also be use in situations where the data are too variable to be modelled by a mathematical function, or where the point data were collected in a manner resulting in very sparse and irregular spatial distributions. This approach will be discussed with respect to the crater density data in Section 5.2 of this report.

In order to examine spatial associations or coincidences between iceberg craters and selected environmental variables in a GIS, data must be converted from points to thematic maps which 'best' represent the spatial data. Given that the thematic maps will be integrated for a multivariate analysis, the original values and the regional data trends must be preserved in the thematic maps. The selection of the interpolation method is critical in this respect. The techniques used in this study were selected for this purpose and the results of the multivariate crater analyses discussed in Section 6.0 reflect the regional data trends for the Grand Banks (see Davis 1986 for a detailed discussion of spatial interpolation).

5.2 Spatial Densities of Iceberg Pits

Figure 3.3 shows the locations where iceberg pits have been observed on the Grand Banks of Newfoundland. In order to translate these individual feature locations into a regional parameter that can then be compared with the various environmental factors, the spatial densities at which craters occur (i.e., craters per km^2) have been calculated for the study area.

The regional distribution of iceberg pit observations on the Grand Banks is highly variable, with strong concentrations of pits in the deeper water areas of northeastern Grand Bank, Downing Basin and the southern portion of Avalon Channel. Very few pits have been observed in the shallower waters on the bank tops. Small-scale variability in the frequency of occurrence of iceberg pits is also strong. For example, within the same water depth range, an area may have a high number of craters while a few kilometers away there may be no evidence of craters in the seabed. This small-scale variability is likely due to a significant change in one or more environmental parameter, such as a change in seabed type from sand or gravel to exposed bedrock.

In addition to strong spatial variability in the iceberg crater data, the available data set is limited by the relatively sparse survey coverage on the Grand Banks of Newfoundland. Figure 3.4 shows the extent of the geophysical data analysed for the various data sources included in the Grand Banks Scour Catalogue. For these reasons, a modified Voronoi polygon approach has been used to calculate the spatial densities of iceberg pits on the Grand Banks.

The crater density calculation is based on a 1 x 1 km grid that was generated for the study area (e.g., Figure 5.2). The Voronoi algorithm in SPANS is then used to produce a base map of 1 x 1 km polygons (e.g., Figure 5.3) covering the entire study area. Each of the polygons are coded with unique Voronoi cell numbers. For example, if there are 100,000 polygons, they would be coded with numbers ranging from 1 to 100,000.

After the initial Voronoi polygon map is produced, the crater point data are used in an 'append class' function whereby a map class value can be appended to a point data set. The output file from this procedure contains the value 1 if a crater occurs within a polygon, together with the corresponding polygon number. At this stage, the densities are calculated by determining if there are 1 or more craters occurring within a cell. This procedure is based on the fact that, if there is more than one data point in a polygon, the points will have the same polygon number.

The polygons with more than 1 crater occurrence are manipulated by a counting routine whereby the number of points that intersect the polygon are summed to give the total count for that polygon. This produces a 1 x 1 km density map for craters where the mapped data are restricted to those polygons actually crossed by the survey lines or covered by the wellsite survey areas. This map is then used to exclude areas that were not surveyed from the data analyses. In addition, areas along the survey line that did not contain a crater were coded as "no crater observed."

The resulting crater density map, classified by crater density, is shown as Figure 5.6. In this figure, surveyed areas where no iceberg craters were found are coded grey. In areas where pits are found, many of the grey polygons have been omitted in order to increase the visual clarity of the map, and to emphasize the pit locations. This is particularly true on northeastern Grand Bank, where seabed data coverage is relatively high.

The feasibility of adjusting the crater densities for the actual area of seabed surveyed in each grid cell was examined as part of this study. For the regional surveys, typical effective swath width data were compiled for each survey line. For the wellsite surveys, estimates of the percentage of seabed surveyed within the outer boundaries of each wellsite were obtained from Terraquest Associates (1994). In general, these estimates show that almost 100% of each wellsite survey area was covered by side scan sonar data. However, it appears that iceberg pits were identified only from sub-bottom profiler records, and not from side scan sonar data, for the wellsite surveys contained in the original Mobil Ice Scour Catalogue (see Table 2.3).

The seabed area covered by the sub-bottom profiler system was reassessed for the wellsites included in the original Mobil database, using a representative swath width of 10 m for the Huntec DTS system (P. Simpkin, pers. comm.) and the survey line lengths given in the Terraquest wellsite survey review report. Although the swath width for a sub-bottom profiler system depends on factors such as aperture and fish height, the value of 10 m is considered to be of the correct order-of-magnitude for most surveys. The revised estimates of seabed coverage are given in Table 5.1; for comparison purposes, the estimates based on side scan sonar data for the wellsites associated with the Mobil update study are also shown.

Table 5.1 clearly indicates that, for a typical wellsite survey, the percentage of seabed covered by sub-bottom profiler data is much less than the seabed coverage when a side scan sonar system is used, assuming the same line spacing. Typically, only 2 to 4 percent of the seabed was surveyed by the sub-bottom profiler system for each wellsite survey.

The effective range and percent seabed coverage data have been combined with the 1 km^2 grid cell system developed for this project, producing a regional map of the data coverage for each individual grid cell. Figure 5.7 shows a variation between roughly 2 and 100% data coverage for the study area, with lower values associated with those surveys where pits were recorded only when seen on the sub-bottom profiler data. The highest values are associated with more recent wellsite surveys, or with regional lines where a sub-bottom profiler system with a large effective range was used (e.g., BIO 70 kHz system). Intermediate values, ranging from 40 to 60%, are generally associated with higher resolution, narrower-range side scan sonar systems.

Table 5.1 also shows the number of craters observed on each of the Mobil wellsite surveys, and the crater densities calculated from the total survey area for each wellsite. Where two values are given, the first value represents the crater density assuming 100% of the seabed has been surveyed, while the second value has been adjusted to reflect the actual data coverage of the seabed. This adjustment was made by simply dividing the unadjusted crater density value by the seabed coverage. In effect, this assumes that the crater density in the unsurveyed portions of each wellsite survey is the same as the crater density in the surveyed portions.

For the Mobil update study, where craters were identified from both sub-bottom profiler and side scan sonar data, the adjusted crater density values are very similar to the unadjusted values. However, the simple linear adjustment described above leads to large changes in the crater densities for the wellsites contained in the original version of the Mobil Ice Scour Catalogue. For these four wellsites, adjusted crater densities reach a maximum value of 29 craters per square kilometer, an order of magnitude greater than the typical densities observed for the wellsites from the Mobil update study.

It is not clear if these high values for the adjusted crater densities from the wellsites in the original Mobil database represent real values, or are simply an artifact of the many assumptions in the simple linear adjustment described above. For example, the effective swath width of a sub-bottom profiler system may be much larger than the 10 m value used in this assessment, or craters may occur in groups, leading to a high degree of correlation between locations of individual pit features.

In order to correctly address this issue, a density kernel function representing a true crater density weighted by seabed coverage should be developed. This approach would involve detailed data analyses and would require a better understanding of the pit formation process. However, the level of effort for this approach is considerable, and is beyond the scope of the current project. All crater densities discussed in the remainder of this report represent values unadjusted for actual seabed data coverage.

Table 5.1
Crater Densities for Wellsite Surveys
Revised Grand Banks Scour Catalogue

Wellsite	Seabed Coverage (%)[2]	Wellsite Area (km^2)[1]	Number of Observed Craters	Crater Density (craters km^{-2})
Mobil Original Study:				
White Rose Flank	2.7	313.3	0	0
Ben Nevis	3.1	89.0	0	0
Hibernia P-15	4.2	30.9	1	0.03 (0.8)
Cumberland	3.0	93.5	82	0.9 (29)
Dana North and South	2.9	193.8	158	0.8 (28)
Hebron	2.7	164.3	0	0
Hibernia North	3.2	69.5	0	0
Nautilus	3.1	87.1	0	0
Ragnar	3.2	89.0	56	0.6 (20)
Rankin	2.8	287.9	0	0
Tempest North	3.0	108.8	0	0
Trave/White Rose	2.9	196.3	0	0
West Hibernia	2.7	63.4	0	0
Mobil Update Study:				
Archer Flank	94	339.1	93	0.3 (0.3)
Bonanza	94	112	139	1.2 (1.3)
Dominion	94	58.4	129	2.2 (2.3)
Linnet	96	200.0	43	0.2 (0.2)
Mara	97	191.0	9	0.05 (0.05)
Saronac	97	171.6	252	1.5 (1.5)
Titus	94	58.4	153	2.6 (2.8)
Voyager	100	62.2	0	0

[1]Wellsite survey areas obtained from NORDCO (1984).

[2]Seabed coverages obtained from Terraquest Associates (1994) for the Mobil update study wellsites. For the Mobil original study wellsites, seabed coverages were estimated using a sub-bottom profiler swath width of 10 m and sub-bottom profiler line kilometres given in Terraquest Associates (1994).

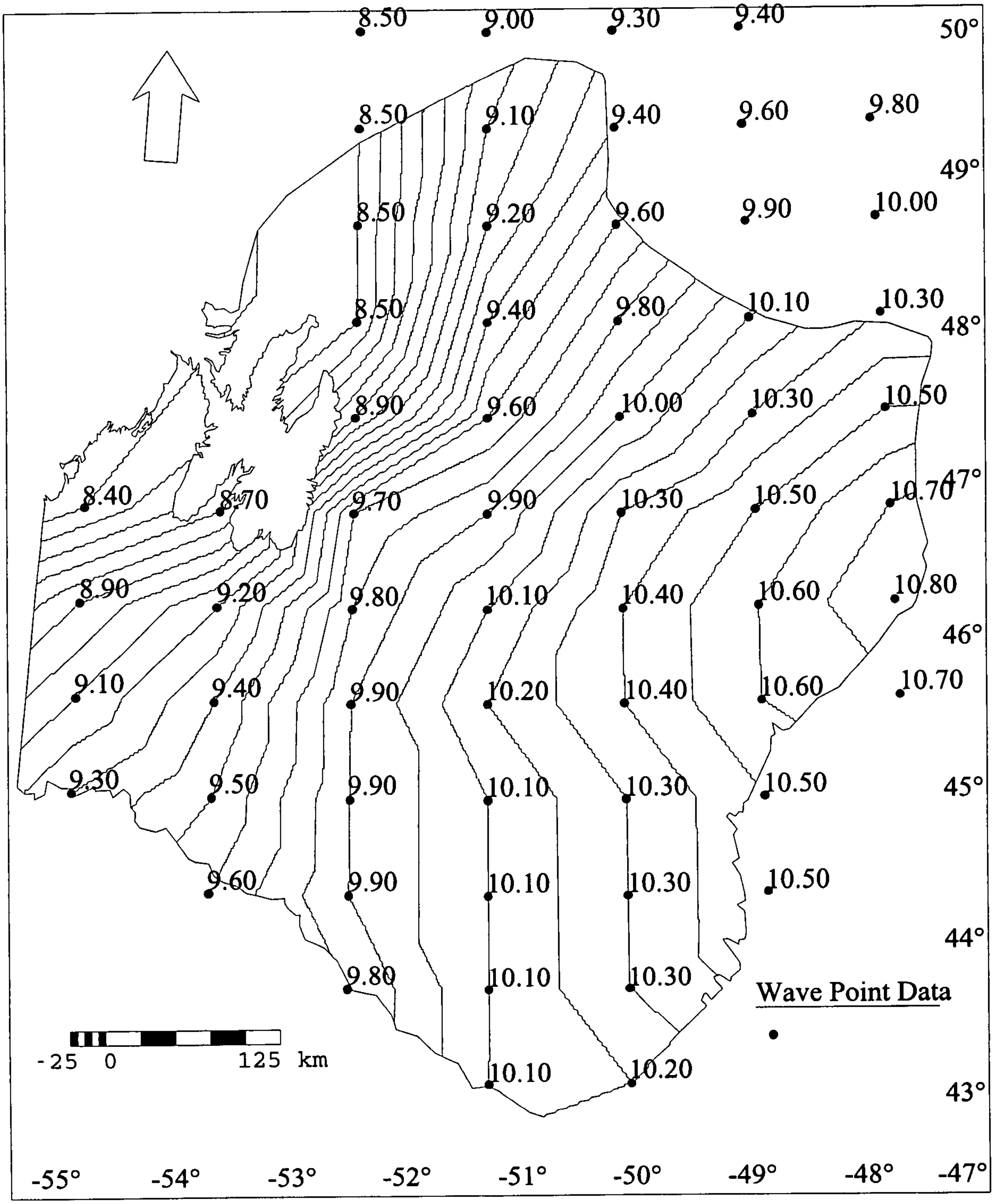


Figure 5.1 **Two-year return period wave height data, showing the model grid points, data values at the grid points and the wave-height contours developed using the linear TIN algorithm in SPANS.**

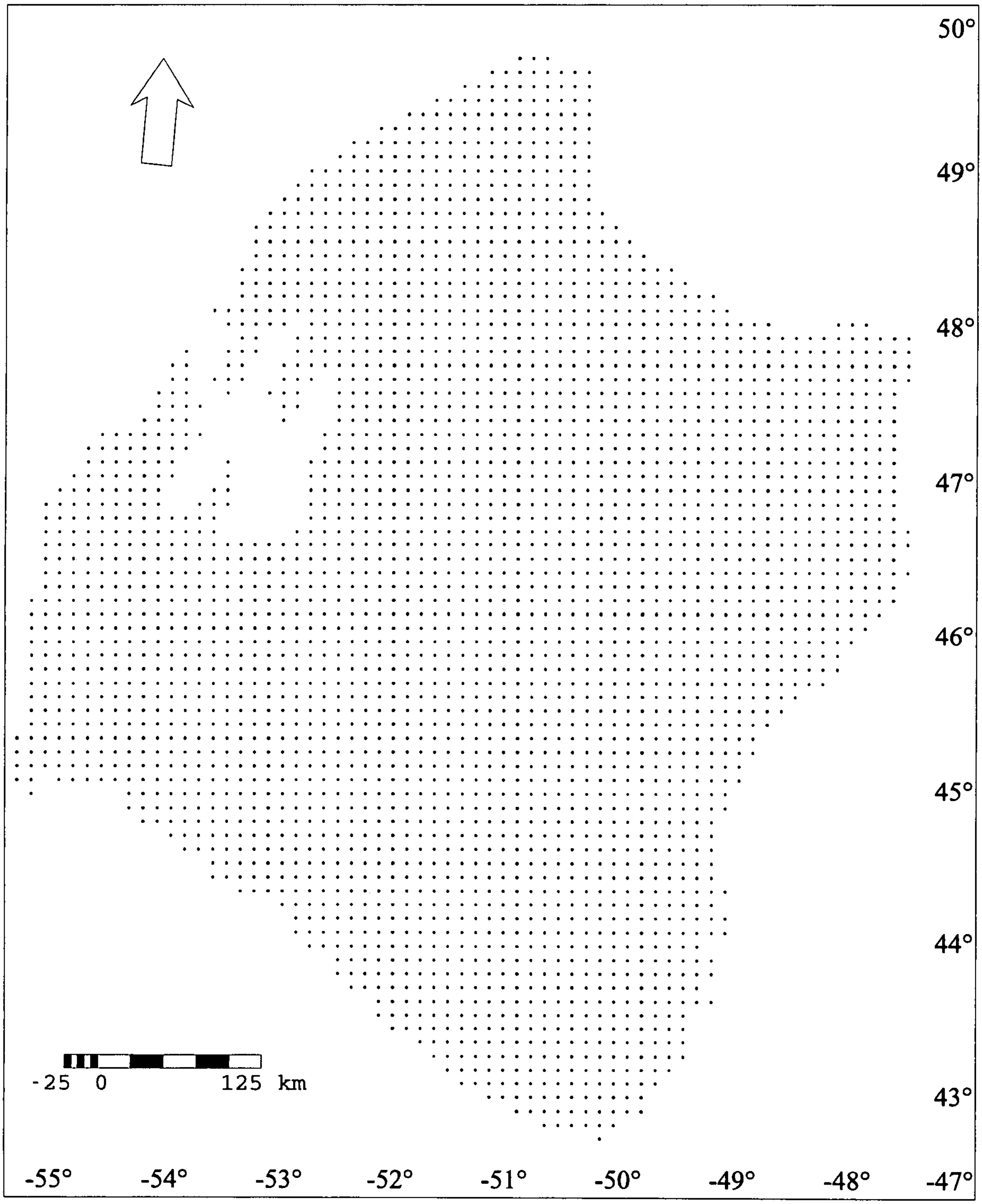


Figure 5.2 **The study area on the Grand Banks of Newfoundland, shown with a regularly-spaced grid of data points.**

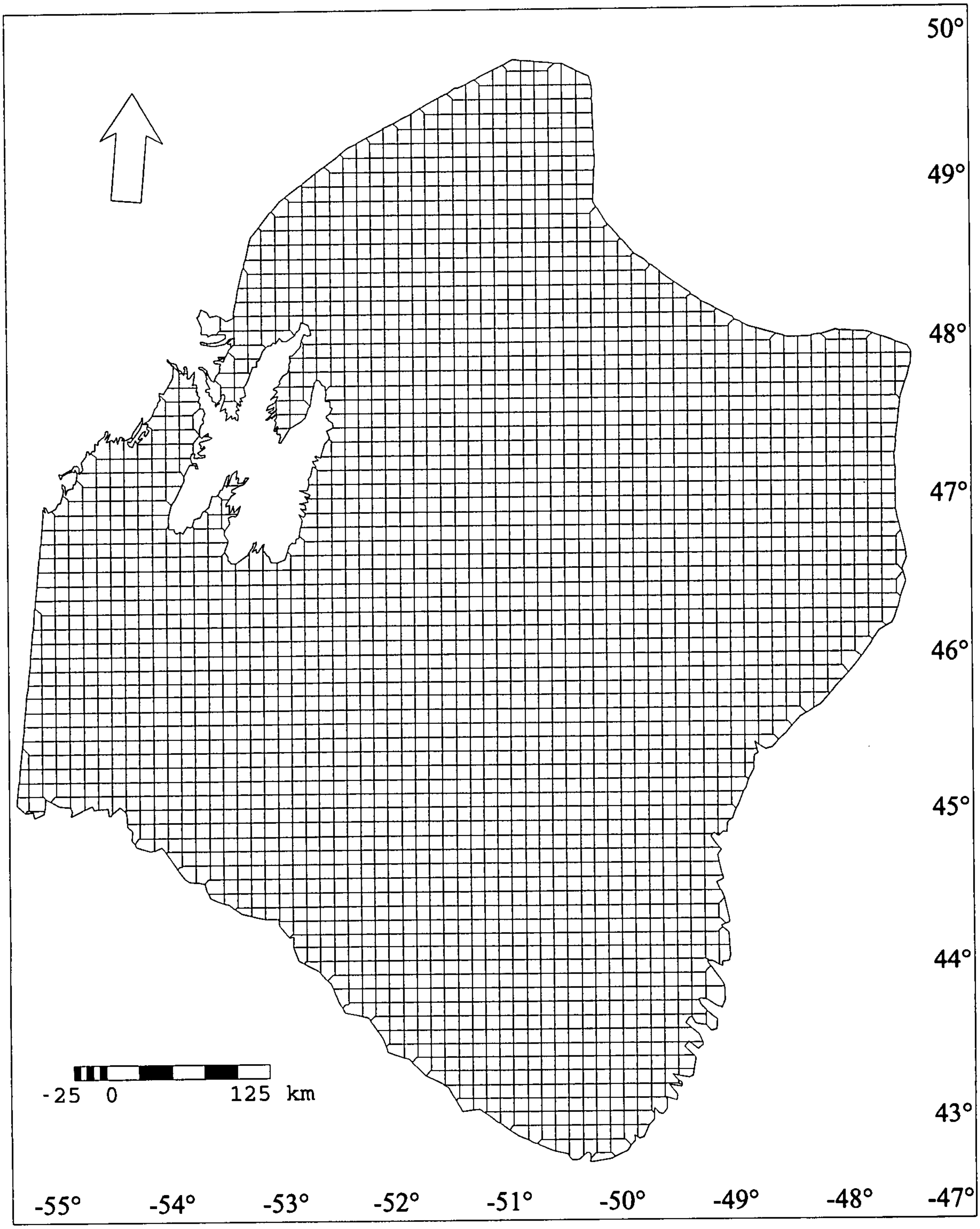


Figure 5.3 **Voronoi polygons resulting from the regularly-spaced grid of data points shown in Figure 5.2.**

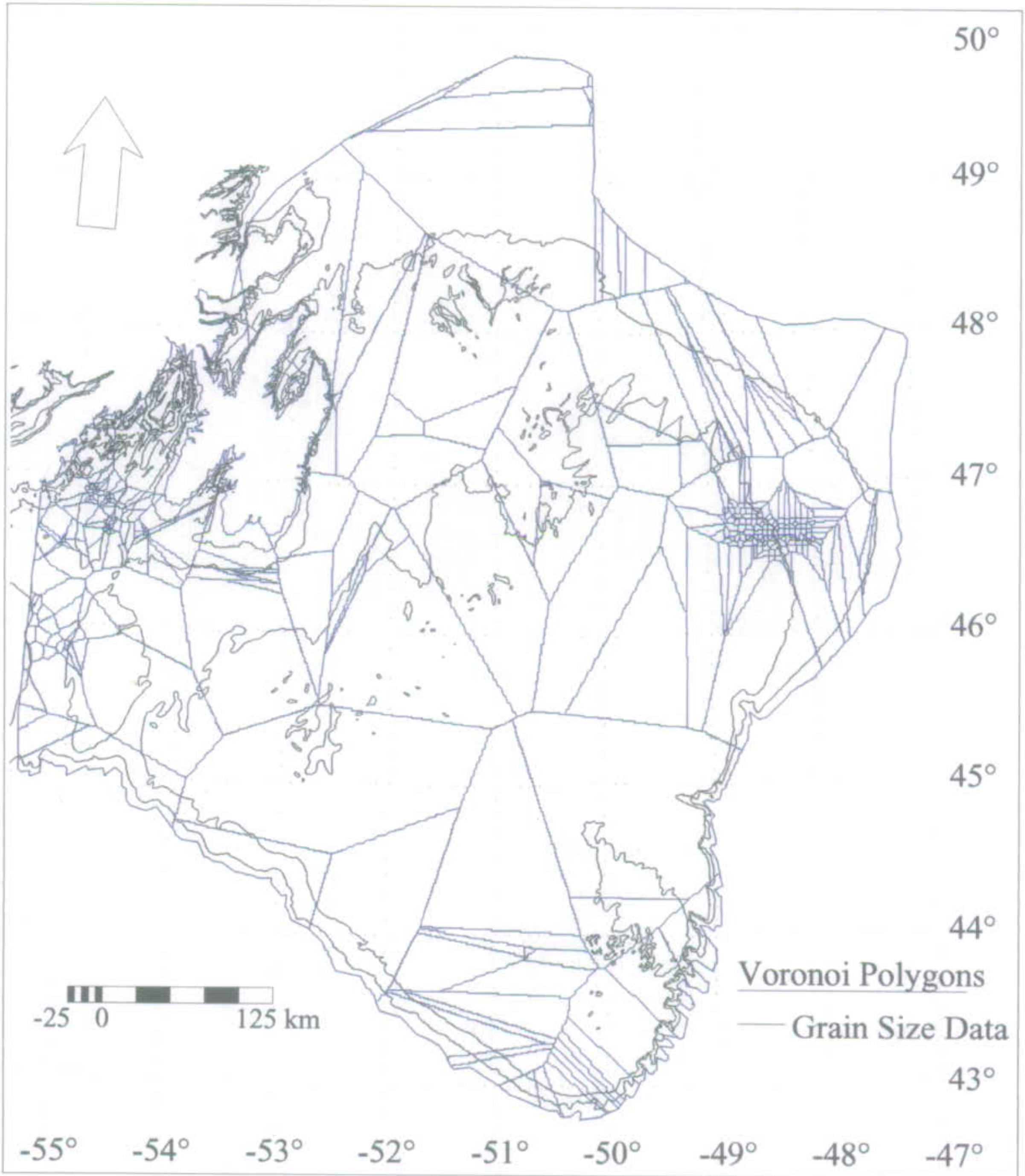


Figure 5.4 **Voronoi polygons derived from the irregularly-spaced point distribution for the surficial sediment grain size samples shown in Figure 4.13.**

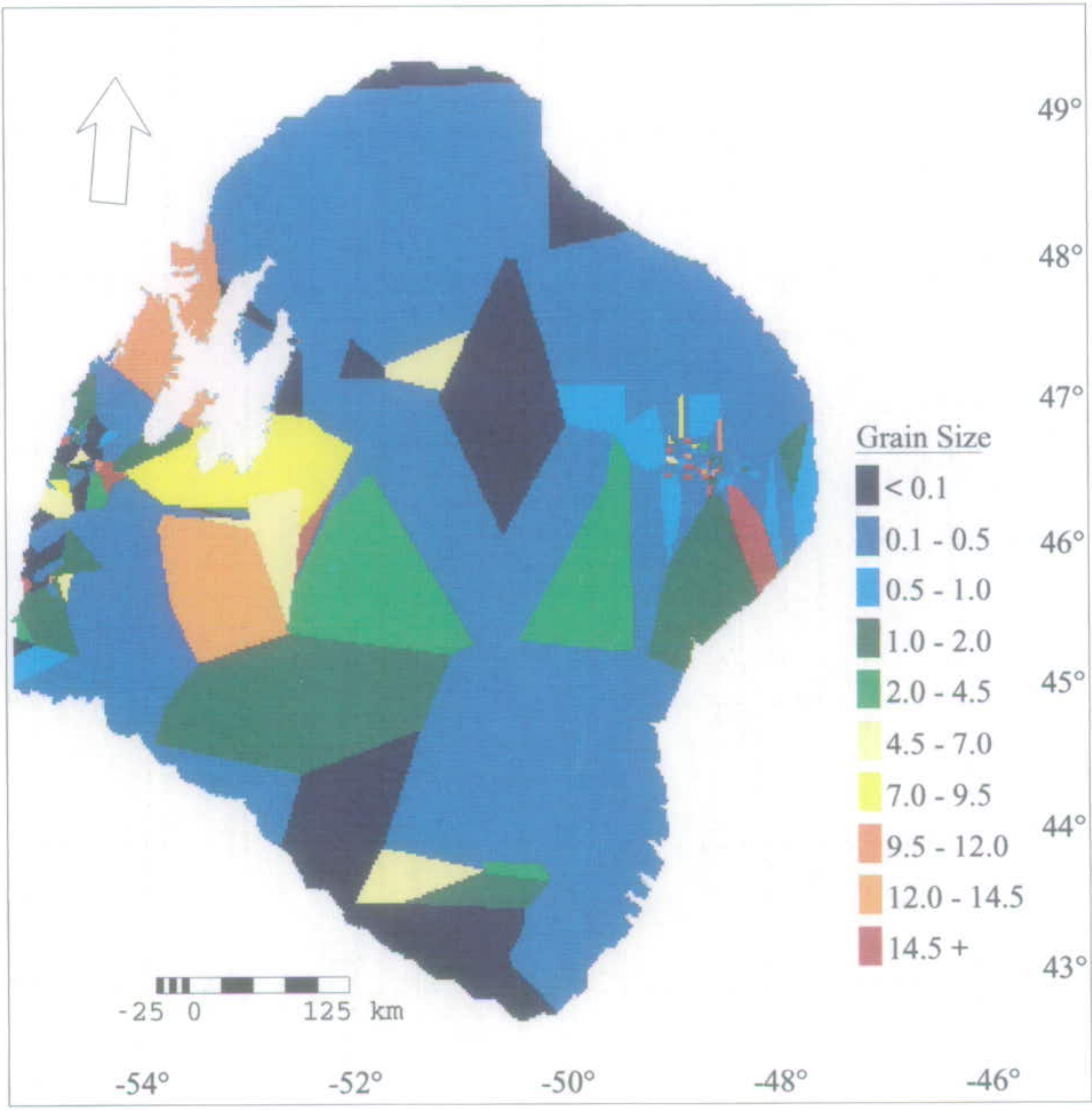


Figure 5.5 **Regional map of surficial sediment grain size (mm), derived using the discrete Voronoi polygon interpolator method (compare with Figure 4.14).**

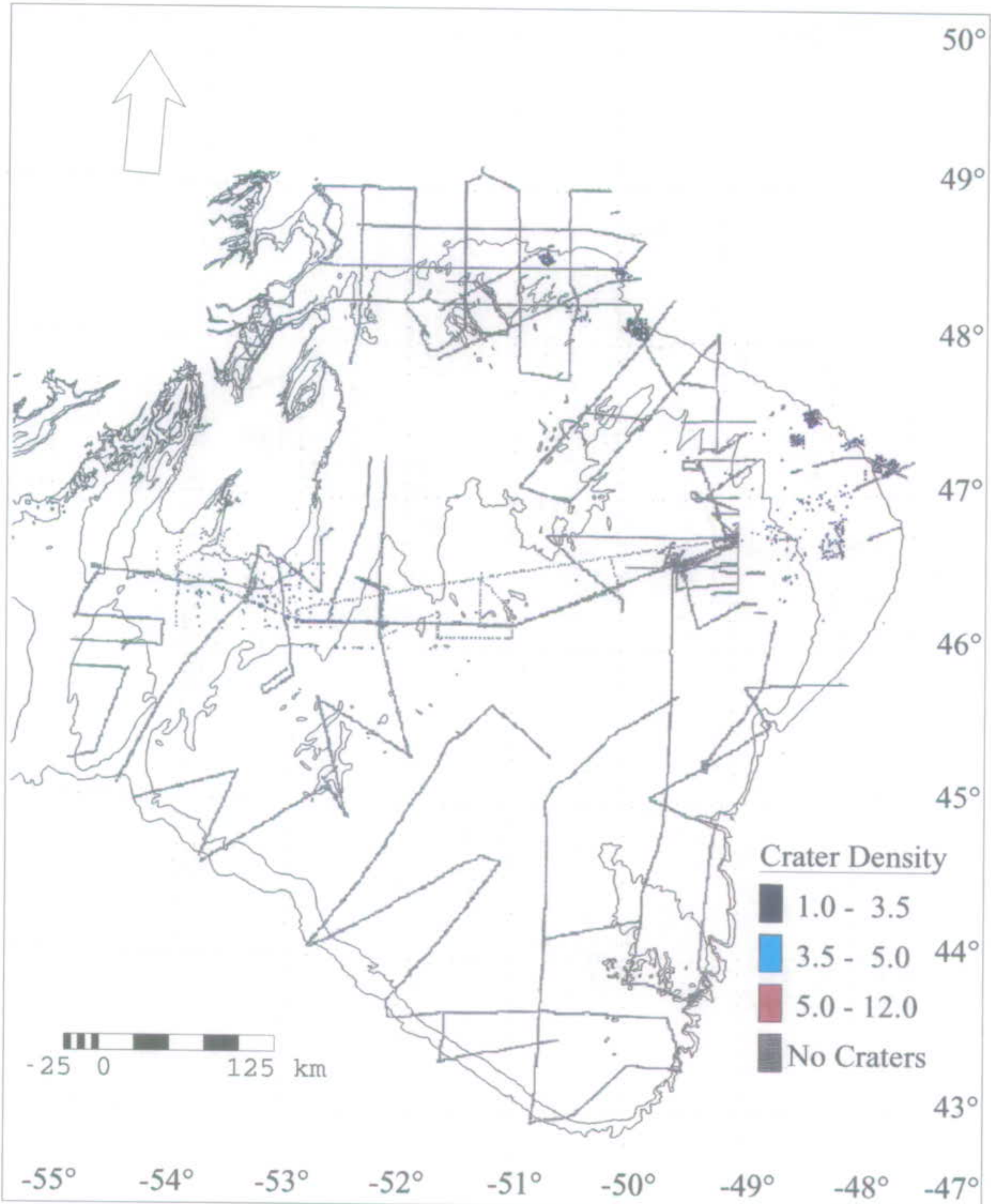


Figure 5.6 **Classified crater densities for the study region (craters km^{-2}). In order to increase clarity, some surveyed areas where no craters were observed have been omitted from this figure.**

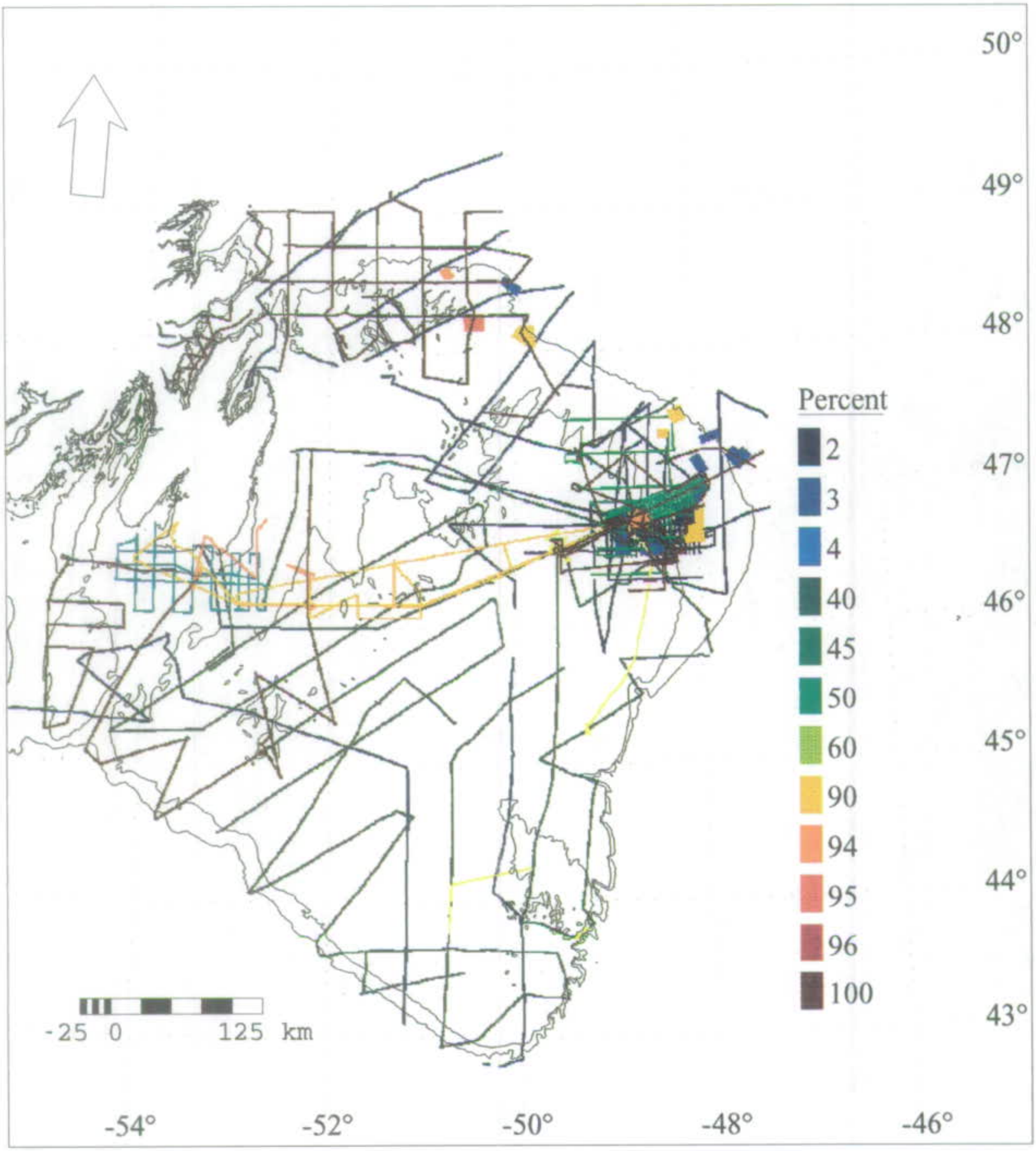


Figure 5.7 Percent seabed coverage for each 1 km^2 grid cell used in this project.

6. EMPIRICAL ICEBERG PIT ANALYSES

6.1 Data-Based Knowledge Acquisition

Evaluation of the relationships between the occurrence of iceberg craters and the various environmental parameters described in Section 4.0 requires that the data be spatially integrated and an appropriate method chosen to determine the relationships between the dependent and independent variables. Conversion of the point data to thematic layers in a GIS is described in Section 5.0 of this report; data integration for analysis purposes was then accomplished using a "unique conditions" overlay routine in the SPANS GIS software. Multivariate analysis of the relationships between the occurrence of iceberg pits (dependent variable) and the various environmental parameters (independent variables) was carried out using regression tree analysis. The methods used to integrate and analyse the data will next be discussed in more detail.

The spatial interpolation methods presented in Section 5.0 were used to create thematic maps for both the iceberg crater data and the environmental parameters used in this project. However, before spatial analysis of the data could proceed, the mapped data needed to be integrated into a single database containing both iceberg crater and environmental parameters. The integrated database was produced using the "unique conditions" mapping procedure in the SPANS GIS software, involving the mathematical overlay of many thematic layers.

When the polygons or areas defining each thematic map are simultaneously overlaid in a GIS, the result is a new set of polygons that are common to all maps used in the overlay operation. The output from this operation is a single thematic map containing polygons representing each unique combination of parameters in the set of overlaid maps. It should be noted that each polygon represents 1 km^2 of the seabed, corresponding to the grid size used to determine the iceberg crater densities.

Each polygon is linked to the attribute table, or database, containing the actual parameter values for all polygons. Therefore, the attribute table represents a comprehensive description of the areal associations between iceberg crater densities and the various environmental parameters. In other words, the attribute table summarizes the spatial associations that can then be analysed for relationships between the iceberg pit parameters and the environmental factors.

The relationships between the occurrence of iceberg pits and the various environmental factors are determined using regression or classification tree methods. These methods subdivide a multivariate data set into mutually exclusive, exhaustive subsets that best describe the variability in the dependent variable (Biggs et al. 1990). The results of a regression tree analysis can be converted to explicit "IF - THEN" rules describing each individual subset of the original database. The "IF - THEN" rules can then be used to examine the relationships between the occurrence of iceberg pits on the Grand Banks of Newfoundland and the various environmental parameters included in this study.

Regression tree methods are useful for analysing data sets consisting of a dependent variable and a set of predictor variables. This approach is also suited to data sets where non-linear interactions between the variables may be important, where data distributions are skewed rather than gaussian, and where the data sets are categorical (i.e., variables are represented by classified rather than continuous data values). Traditional statistical analysis methods do not produce reliable results under these conditions.

The regression tree model used in this study was developed by Biggs et al. (1990) and is commonly referred to as Knowledge Seeker (KS). Biggs et al. (1990) describe KS as a regression tree algorithm "*which recursively splits each subset (node) into k new nodes (where 2≤ k ≤ c), starting with all the observations at the initial node. This process continues until no more splits can be found. At each node all the predictor variables are considered in turn as candidates to split the node. The best k-way split of each variable is found, then the significance of that split is used to rank the variables on how well they split the node.*"

After the attribute, or unique conditions, table was created using SPANS GIS, it was imported into KS for analysis purposes. The rules generated by KS represent the unique relationships between the dependent and independent variables in the attribute database. In this study, both the dependent and the predictor (independent) variables have been classified; thus, the rules represent relationships between classes of data. The result for the occurrence of a category is expressed as an empirical probability or percentage. For example, a rule derived for the occurrence of iceberg craters may appear as:

Rule 1:	IF		
		Isobath = [50,80)	
		Tides = [10,55)	
	THEN		
		Craters = Absent	99.7%
		Craters = Present	0.3%

This rule indicates that, within the unique conditions database, in areas where water depths are between 50 and 80 meters and the tidal amplitude is between 10 and 55 cm, iceberg craters are absent 99.7% of the time and present 0.3% of the time. Percentage values refer to the sampled area of the seabed (i.e., surveyed area) corresponding to the class definitions defined by each rule.

The Knowledge Seeker software uses an algorithm that produces the best set of class intervals on which to split a particular node. Thus, the data intervals reflected in each rule are adapted to suit the attributes of the data associated with the node being divided. In the above example, bathymetry data were classified into 10 m intervals for water depths above 100 m (Section 4.2.1) prior to using the KS routine. KS then produced the split at 80 m as the best choice to fit all the available data, giving a water depth class interval from 50 to 80 m. For those areas of the seabed between 50 and 80 m water depth, tidal amplitude was found to be the next best predictor (after bathymetry) of the presence of iceberg craters. Knowledge Seeker then selected a second-level split in the data based on tidal amplitude, with a data interval between 10 and 55 cm.

The KS approach provides for the inclusion of continuous or categorical dependent and predictor variables. Continuous variables are reduced to a restricted number of ordinal classes. KS can deal with three types of predictor (independent) variables:

- monotonic, where variables can be categorized on an ordinal scale;
- free, where variable categories are nominal; or
- floating, where all variable categories are monotonic with the exception of one.

The third type of predictor variable can be used to include missing or unknown values in the analysis. For example, variables which include values coded as missing can be assigned to the categories which they most closely resemble.

The predictor variables (environmental parameters) used in this study fall into the first two categories. Most of the data sets are monotonic, with predictor variables varying over a continuous range of numerical values. The surficial geologic unit data represent a free parameter, with allowable parameter values limited to a discrete set of nominal values (Grand Banks Sand and Gravel, Placentia Clay, Adolphus Sand, Downing Silt or Grand Banks Drift). The dependent variable, crater density, is again a monotonic parameter, with possible data values limited to ordinal numbers. Given that the iceberg crater and environmental variables contain nominal, continuous and ordinal data types, KS provides an appropriate analysis method for this project.

The KS program utilizes the chi-squared statistic to test the significance of categorical associations while the F-statistic is used to compare the variance of two or more groups of data. KS also provides very comprehensive testing procedures for determining the statistical significance of a split in the data set based on the predictor variables. If the best split is not found to be statistically significant, then the data partition or condition is rejected.

The KS method uses a "Bonferri adjustment factor" that accounts for the problem of testing significance on the grouping of categories with the highest level of significance.

This factor sets the significance level for the most statistically important groups such that the Type I error rate (e.g., $\alpha = 0.05$) is maintained throughout the analysis. This provides an important control on the data analysis whereby KS "*can be confidentially used with small categorical data sets and will not, on average, detect spurious relationships between the response and predictor variables more often than the specified Type I error rate, α*" (Biggs et al. 1990). This approach allows the numerous inter-relationships between the predictor variables to be considered in the analysis process (i.e., sediment transport rate is a non-linear function of water depth, current speed, wave height, wave period and sediment grain size).

6.2 Factors Governing the Presence of Iceberg Pits

Calculation of the spatial densities of iceberg craters on the Grand Banks of Newfoundland is discussed in Section 5.2 of this report. The observed densities, classified using EDA techniques, are shown in Figure 5.6. Observed crater densities range from zero to 12 pits per square kilometre, with over 95% of the surveyed areas indicating no iceberg craters on the seabed records.

The available environmental data are described in Section 4.0 of this report. For the purposes of this study, twelve environmental parameters have been used in the empirical analyses:

1. water depth
2. iceberg density
3. surficial geologic unit
4. sediment grain size
5. seabed aspect (direction of dip)
6. tidal amplitude
7. current speed (mean currents)
8. current direction (mean currents)
9. wave height (2 yr return period)
10. wave period (2 yr return period)
11. sediment transport rate
12. seabed stress ratio

The main purpose of the empirical pit analyses described in this report is to use the available data to determine the strongest relationships between the occurrence of iceberg pits and the various environmental parameters thought to influence pit formation. As a first assessment, the crater densities shown in Figure 5.6 have been simply re-classified to reflect the presence or absence of iceberg craters on the seabed record. More detailed analyses based on classified crater densities will be discussed in Section 6.3 of this report.

An important issue with respect to the iceberg pit database concerns the accuracy of using a limited sample of the seabed to represent the characteristics of the entire study area. For this project, the sample size is limited by the area of the seabed that has been surveyed and analysed for seabed ice-contact features. The statistical characteristics of the iceberg pit population represented by this sample may or may not be representative of the entire iceberg pit population on the Grand Banks of Newfoundland.

In the analyses described in this report, it has been assumed that the available data can be used as an unweighted representation of the total population of iceberg pits on the Grand Banks. However, it should be remembered that the actual areas of the seabed surveyed are strongly biased towards northeastern Grand Bank. Thus, the results of the analyses described herein may be more representative of that region than of the entire study area.

As a preliminary step in the assessment process, the twelve environmental parameters have been ranked in terms of their relative success as single predictors of the presence of iceberg craters on the seabed. This ranking is given in the centre column of Table 6.1. Of the twelve predictors, water depth is the strongest single predictor of the presence or absence of pit features, while seabed aspect is the weakest. A Type I error rate of 0.01 (99% confidence), together with a 91% correct classification rate, is associated with these rankings.

The Knowledge Seeker approach requires the primary predictor variable, on which the initial split of the data is based, to be specified by the user. Using water depth as the primary predictor for the presence of iceberg pits, the resulting set of "IF-THEN" rules is presented in Table 6.2. Of the 48 rules presented, the first is the most significant in terms of explaining the variability in the data, while the last is the least important. However, all rules are significant, with a Type I error rate of 0.01 maintained throughout this analysis. The second, third and fourth-order predictors for each water depth class interval are presented in Table 6.3.

Several of the environmental parameters listed in Table 6.1 as strong predictors, when considered alone, of the presence of iceberg pits do not appear in the rules listed in Table 6.2 (e.g. seabed stress ratio, surficial geology). The rankings presented in Table 6.1 consider the relative importance of each environmental parameter on an individual basis; interactions between variables are not included. Thus, this simple ranking evaluates the relative strengths of each parameter as if it was the only factor under consideration in the prediction of the presence or absence of iceberg pits on the seabed.

Conversely, the detailed rules presented in Table 6.2 and summarized in Table 6.3 are based on the full Knowledge Seeker analysis procedure, where interactions between variables are considered. Thus, the result that tidal amplitude, iceberg density, sediment grain size and wave height appear as second-order predictor variables (depending on the water depth class interval) is intrinsically linked to the choice of water depth as the primary predictor variable for the presence of iceberg craters.

In order to compare these results with the rules that would result from using a different environmental parameter as the primary predictor variable, the Knowledge Seeker analyses were rerun with seabed stress ratio, iceberg density and surficial geologic unit chosen respectively as the primary predictor variable. The results of the KS analyses based on seabed stress ratio as the primary predictor are summarized in Table 6.4.

Tables 6.3 and 6.4 show several interesting features. Firstly, not all twelve environmental parameters considered in this study appear in the "IF-THEN" rules for the presence of iceberg pits. When water depth is used as the primary predictor variable, seabed stress ratio and surficial geologic unit do not appear as significant predictor variables. Similarly, when seabed stress ratio is used as the primary predictor, surficial geologic unit, current speed, current direction, wave period and sediment transport rate are not included in the analysis results. Water depth appears only as a third-order predictor variable in one stress ratio class interval.

Secondly, the relative importance of a specific environmental parameter in predicting the presence of iceberg pits on the seabed depends on the choice of the primary predictor variable. As an example, when water depth is used as the primary predictor variable, grain size is important as a second-order predictor, while it appears only as a third-order predictor when seabed stress ratio is the primary predictor variable.

It is clear from these results that not all of the environmental parameters considered in this study are required in order to explain the spatial variability in the iceberg crater data. It is also clear that this variability can be explained in more than one manner, depending on the choice of primary predictor variable.

The differences between the results summarized in Table 6.3 and Table 6.4 can be explained in terms of spatial correlations and non-linear interactions between the various environmental parameters. Some of the variables (e.g., water depth and surficial geologic unit) may be highly correlated in a spatial sense. For example, the boundaries between the various surficial geologic units may closely follow the major bathymetric contours (compare Figure 4.9 with Figure 4.1). Other variables, such as seabed stress ratio and sediment transport rate, may effectively integrate the spatial variability in other, simpler variables. Both the seabed stress ratio and the sediment transport rate are calculated from water depth, wave height, wave period, current speed and sediment grain size information.

For this project, water depth has been retained as the primary predictor variable. Although other variables such as seabed stress ratio, iceberg density or surficial geologic unit could be effectively used instead of water depth, the spatial variability in these parameters strongly mirrors the spatial variability in water depth. In addition, the water depth database is relatively complete, with good spatial coverage of the study area. Water depth is also a relatively simple parameter, without the inherent uncertainties associated with the calculation of seabed stresses, the interpretation and analysis of iceberg observations or the regional mapping of surficial geologic unit.

The detailed rules presented in Table 6.2 show some general trends in the occurrence of iceberg craters, although variability in the data is high. In general, iceberg pits are found less frequently in shallower waters above about 90 m. Few iceberg pits are found in waters deeper than 250 m, although significant exceptions occur (see Rule 40 and Rule 46).

The rules given in Table 6.2 show that the relative importance of the various environmental parameters as predictors of the presence of iceberg pits varies strongly with water depth. Between 90 and 150 m, iceberg density is the second most important predictor of the presence of iceberg pits, after water depth. A weak trend is present, with the occurrence of iceberg pits generally increasing as the iceberg density increases. The relationship between pit occurrence and the third-order predictors (wave period and tidal amplitude) is not intuitive, with the highest occurrences of iceberg pits found at intermediate wave periods and tidal ranges.

The greatest numbers of iceberg craters are found in the 150 to 200 m water depth range, with a spatially-averaged occurrence rate of 11.9 % (i.e., iceberg craters are present in 11.9 % of the 1 km^2 grid cells representing the surveyed areas of the seabed between 150 and 200 m water depth). In this water depth class interval, sediment grain size becomes the second most important predictor of the presence of iceberg pits, with tidal amplitude, iceberg density and wave height the third-order predictors. Again, the relationships between pit occurrence and these variables are not intuitive, with no clear trends emerging from the empirical rules in this water depth range.

Between 200 and 250 m, wave height is the second-order predictor for the presence of iceberg pits, with seabed aspect, current speed and sediment transport rate becoming the third-order predictor variables. In a general sense, the occurrence rate for iceberg pits increases with increasing wave height. However, the variability in the pit data also increases as wave height increases, with seabed areas with the same wave height value showing widely disparate values for pit occurrence (e.g., compare rule 33 with rule 34 and rule 36 with rule 37). Seabed mobility may be an important factor, perhaps leading to the preservation of iceberg pit features in regions with lower sediment transport rates.

In water depths greater than 250 m, sediment grain size is again the second-order predictor of the presence of iceberg pits. Iceberg density and current direction become the third-order predictor variables. Again, the relationships between the pit occurrence rate and the predictor variables are not intuitive, with no clear trends emerging.

6.3 Factors Governing the Spatial Density of Iceberg Pits

The analyses presented in Section 6.2, describing the empirical "IF-THEN" rules for the presence of iceberg pits on the Grand Banks of Newfoundland, have been repeated using the classified iceberg crater densities shown in Figure 5.6 of this report. The available iceberg crater data have been classified into four data intervals using the number of crater observations in each 1 km^2 grid cell: no craters, 1 to 3.5 craters km^{-2}, 3.5 to 5 craters km^{-2}, and 5 to 12 craters km^{-2}. The detailed rules for the classified crater densities are presented in Table 6.5, with the summary of the second-, third- and fourth-order predictor variables given as Table 6.6.

The right-hand column of Table 6.1 shows the relative ranking of the various environmental parameters as single predictors of the presence of iceberg pits, when the classified iceberg pit density data are used. This ranking is only slightly different from that for the unclassified density data shown in the centre column of this table, with wave height and wave period switched in terms of relative importance.

The summaries presented in Table 6.6 and Table 6.3 for the classified and unclassified pit data, respectively, show only minor changes in the third- and fourth-order predictor variables. The second-order predictor variables remain unchanged. For the classified pit density data and the 150 to 200 m water depth range, wave period and seabed aspect are more important predictors of the occurrence of iceberg pits than for the unclassified case previously described. Wave period also replaces iceberg density and current direction as third-order predictors for waters depths greater than 250 m, and the 80 to 90 m water depth class interval has disappeared from the analysis results.

A closer comparison of the detailed rules presented in Table 6.5 and Table 6.2 shows considerable similarity between the rules for the classified and unclassified crater densities in water depths up to 150 m. In water depths shallower than 90 m, pit occurrence increases slightly with an increase in tidal amplitude. Between 90 and 150 m, pit occurrence generally increases as iceberg density increases, with perhaps a third-order trend of increasing pit occurrence with increasing tidal amplitude.

In the 150 to 200 m water depth range, sediment grain size is again the second-order predictor of the occurrence of iceberg pits, with wave period added to the previous list of third-order predictor variables. Again, no clear trends relating pit occurrence to changes in the predictor variables are evident from the empirical rules in this water depth range.

Between 200 and 250 m water depth, wave height is again the second-order predictor variable, with seabed aspect, current speed and transport rate as the third-order predictors. Seabed aspect also appears as a fourth-order predictor variable for the classified pit density data set. As for the unclassified data, a weak trend can be seen with the occurrence of iceberg pits increasing with increasing wave height. Again, variability in the data is high.

In the deepest waters below 250 m, wave period replaces iceberg density and current direction as the third-order predictor. No clear trends can be seen in the relationships between the pit occurrence rate and the predictor variables.

6.4 Effects of Seabed Mobility

As discussed in Section 4.3.5 of this report, seabed mobility may affect the persistence and characteristics of ice-contact features on the seabed. In areas of high seabed mobility or high sedimentation rates, seabed ice-contact features may be erased from the seabed over time or may appear only as buried features. Recently-formed features may appear degraded and be mistaken for relict features. Finally, infilling or reworking may significantly reduce the measured dimensions, particularly pit or scour depth, from the original dimensions of the newly-formed feature.

Table 6.3 and Table 6.4 of this report summarize the important environmental parameters as related to the occurrence of iceberg pits on the Grand Banks of Newfoundland. Table 6.3 shows that water depth, sediment grain size, wave height, wave period, current speed and current direction are all important parameters in predicting the occurrence of iceberg pits. When seabed stress ratio is used as the primary predictor (Table 6.4), water depth, sediment grain size, wave period, current speed and current direction all play a less important role as predictor variables. These variables, along with wave height, are the input variables to the calculation of the sediment mobility parameters used in this study (seabed stress ratio and sediment transport rate). This suggests that, in addition to representing a surrogate variable for water depth, seabed mobility is itself an important parameter affecting the occurrence of iceberg pits.

Ideally, it would be possible to quantitatively assess the effects of seabed mobility on the occurrence of iceberg pits through selective data analysis techniques. In practice, this is difficult to achieve. For this project, an attempt was made to assess the effects of seabed mobility by excluding those areas of the seabed where the stress ratio was greater than 1000 from the data analyses. In effect, rules would then be derived for only those areas of the seabed where the effects of sediment mobility are minimal. Unfortunately, due to the close correlation between seabed stress ratio and water depth, this approach led to insufficient data in shallower water areas to derive rules.

Table 6.1
Ranked Predictor Variables for the Occurrence of Iceberg Pits
Revised Grand Banks Scour Catalogue

Environmental Parameter	Ranking Presence/Absence	Ranking Density-classified
Water Depth	1	1
Seabed Stress Ratio	2	2
Iceberg Density	3	3
Surficial Geology	4	4
Transport Rate	5	5
Tidal Amplitude	6	6
Current Direction	7	7
Grain Size	8	8
Wave Height	9	10
Wave Period	10	9
Current Speed	11	11
Seabed Aspect	12	12

Table 6.2
"IF-THEN" Rules for the Presence of Iceberg Pits
Revised Grand Banks Scour Catalogue

RULE 1 IF
- Isobath = [50,80)
- Tides = [10,55)

THEN
- Craters = Absent 99.7%
- Craters = Present 0.3%

RULE 2 IF
- Isobath = [50,80)
- Tides = [55,76]

THEN
- Craters = Absent 94.7%
- Craters = Present 5.3%

RULE 3 IF
- Isobath = [80,90)

THEN
- Craters = Absent 98.0%
- Craters = Present 2.0%

RULE 4 IF
- Isobath = [90,150)
- Iceberg = <1

THEN
- Craters = Absent 100.0%

RULE 5 IF
- Isobath = [90,150)
- Iceberg = 1-2
- Waveprd2 = [13.5,14)

THEN
- Craters = Absent 100.0%

RULE 6 IF
- Isobath = [90,150)
- Iceberg = 1-2
- Waveprd2 = [14,14.2)

THEN
- Craters = Absent 69.6%
- Craters = Present 30.4%

RULE 7 IF
- Isobath = [90,150)
- Iceberg = 1-2
- Waveprd2 = [14.2,14.9]

THEN
- Craters = Absent 99.1%
- Craters = Present 0.9%

RULE 8 IF
- Isobath = [90,150)
- Iceberg = 2-3 to 5-6
- Tides = [10,40)

THEN
- Craters = Absent 89.7%
- Craters = Present 10.3%

RULE 9 IF
- Isobath = [90,150)
- Iceberg = 2-3 to 5-6
- Tides = [40,55)

THEN
- Craters = Absent 97.9%
- Craters = Present 2.1%

RULE 10 IF
- Isobath = [90,150)
- Iceberg = 2-3 to 5-6
- Tides = [55,65)

THEN
- Craters = Absent 66.7%
- Craters = Present 33.3%

RULE 11 IF
- Isobath = [90,150)
- Iceberg = 2-3 to 5-6
- Tides = [65,76]

THEN
- Craters = Absent 82.5%
- Craters = Present 17.5%

RULE 12 IF
Isobath = [90,150)
Iceberg = 6-7
THEN
Craters = Absent 42.9%
Craters = Present 57.1%

RULE 13 IF
Isobath = [150,200)
Grainsize = [0.01,0.19)
THEN
Craters = Absent 90.1%
Craters = Present 9.9%

RULE 14 IF
Isobath = [150,200)
Grainsize = [0.19,0.308)
Tides = [10,34)
THEN
Craters = Absent 60.0%
Craters = Present 40.0%

RULE 15 IF
Isobath = [150,200)
Grainsize = [0.19,0.308)
Tides = [34,37)
THEN
Craters = Absent 92.9%
Craters = Present 7.1%

RULE 16 IF
Isobath = [150,200)
Grainsize = [0.19,0.308)
Tides = [37,44)
Aspect = No Aspect
THEN
Craters = Absent 49.4%
Craters = Present 50.6%

RULE 17 IF
Isobath = [150,200)
Grainsize = [0.19,0.308)
Tides = [37,44)
Aspect = 0-45 to 315-360
THEN
Craters = Absent 95.8%
Craters = Present 4.2%

RULE 18 IF
Isobath = [150,200)
Grainsize = [0.19,0.308)
Tides = [44,76]
THEN
Craters = Absent 99.0%
Craters = Present 1.0%

RULE 19 IF
Isobath = [150,200)
Grainsize = [0.308,1.347)
THEN
Craters = Absent 89.6%
Craters = Present 10.4%

RULE 20 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = <1 or 1-2
THEN
Craters = Absent 100.0%

RULE 21 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = 2-3
THEN
Craters = Absent 32.7%
Craters = Present 67.3%

RULE 22 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = 3-4 to 6-7
THEN
Craters = Absent 82.5%
Craters = Present 17.5%

RULE 23 IF
Isobath = [150,200)
Grainsize = [7.013,16.912)
Wavehgt2 = [8.4,9.1)
THEN
Craters = Absent 93.8%
Craters = Present 6.2%

RULE 24 IF
Isobath = [150,200)
Grainsize = [7.013,16.912)
Wavehgt2 = [9.1,9.5)
THEN
Craters = Absent 61.1%
Craters = Present 38.9%

RULE 25 IF
Isobath = [150,200)
Grainsize = [7.013,16.912)
Wavehgt2 = [9.5,10.5)
THEN
Craters = Absent 94.1%
Craters = Present 5.9%

RULE 26 IF
Isobath = [150,200)
Grainsize = [7.013,16.912)
Wavehgt2 = [10.5,10.7]
THEN
Craters = Absent 66.7%
Craters = Present 33.3%

RULE 27 IF
Isobath = [150,200)
Grainsize = [16.912,29.041]
THEN
Craters = Absent 100.0%

RULE 28 IF
Isobath = [200,250)
Wavehgt2 = [8.4,9.1)
THEN
Craters = Absent 96.3%
Craters = Present 3.7%

RULE 29 IF
Isobath = [200,250)
Wavehgt2 = [9.1,9.5)
Aspect = No Aspect
THEN
Craters = Absent 69.1%
Craters = Present 30.9%

RULE 30 IF
Isobath = [200,250)
Wavehgt2 = [9.1,9.5)
Aspect = 0-45 to 315-360
THEN
Craters = Absent 99.1%
Craters = Present 0.9%

RULE 31 IF
Isobath = [200,250)
Wavehgt2 = [9.5,9.8)
Curspeed = 0-5 or 5-10
THEN
Craters = Absent 96.4%
Craters = Present 3.6%

RULE 32 IF
Isobath = [200,250)
Wavehgt2 = [9.5,9.8)
Curspeed = 10-15 or 15-20
THEN
Craters = Absent 53.8%
Craters = Present 46.2%

RULE 33 IF
Isobath = [200,250)
Wavehgt2 = [9.8,10)
Transrate = Zero or 1-10
THEN
Craters = Absent 27.5%
Craters = Present 72.5%

RULE 34 IF
Isobath = [200,250)
Wavehgt2 = [9.8,10)
Transrate = 10-100 to 10000+
THEN
Craters = Absent 100.0%

RULE 35 IF
Isobath = [200,250)
Wavehgt2 = [10,10.3)
THEN
Craters = Absent 100.0%

RULE 36 IF
Isobath = [200,250)
Wavehgt2 = [10.3,10.6)
Transrate = Zero
THEN
Craters = Absent 26.7%
Craters = Present 73.3%

RULE 37 IF
Isobath = [200,250)
Wavehgt2 = [10.3,10.6)
Transrate = 1-10 to 10000+
THEN
Craters = Absent 100.0%

RULE 38 IF
Isobath = [200,250)
Wavehgt2 = [10.6,10.7]
THEN
Craters = Absent 83.3%
Craters = Present 16.7%

RULE 39 IF
Isobath = [250,500]
Grainsize = [0.01,0.104)
Iceberg = <1 to 3-4
THEN
Craters = Absent 100.0%

RULE 40 IF
Isobath = [250,500]
Grainsize = [0.01,0.104)
Iceberg = 4-5
THEN
Craters = Absent 50.0%
Craters = Present 50.0%

RULE 41 IF
Isobath = [250,500]
Grainsize = [0.01,0.104)
Iceberg = 5-6 or 6-7
THEN
Craters = Absent 100.0%

RULE 42 IF
Isobath = [250,500]
Grainsize = [0.104,0.19)
THEN
Craters = Absent 96.5%
Craters = Present 3.5%

RULE 43 IF
Isobath = [250,500]
Grainsize = [0.19,0.233)
THEN
Craters = Absent 90.9%
Craters = Present 9.1%

RULE 44 IF
Isobath = [250,500]
Grainsize = [0.233,0.39)
THEN
Craters = Absent 100.0%

RULE 45 IF
Isobath = [250,500]
Grainsize = [0.39,0.486)
Curdir = 0-45 to 90-135
THEN
Craters = Absent 100.0%

RULE 46 IF
Isobath = [250,500]
Grainsize = [0.39,0.486)
Curdir = 135-180 to 315-360
THEN
Craters = Absent 26.7%
Craters = Present 73.3%

RULE 47 IF
Isobath = [250,500]
Grainsize = [0.486,16.912)
THEN
Craters = Absent 100.0%

RULE 48 IF
Isobath = [250,500]
Grainsize = [16.912,29.041]
THEN
Craters = Absent 100.0%

Table 6.3
Predictor Variables for the Presence of Iceberg Pits
Revised Grand Banks Scour Catalogue

Water Depth Interval (m)	Second-Order Predictor Variables	Third-Order Predictor Variables	Fourth-Order Predictor Variables
50-80	Tidal Amplitude		
80-90			
90-150	Iceberg Density	Wave Period Tidal Amplitude	
150-200	Grain Size	Tidal Amplitude Iceberg Density Wave Height	Seabed Aspect
200-250	Wave Height	Seabed Aspect Current Speed Transport Rate	
250-500	Grain Size	Iceberg Density Current Direction	

Table 6.4
Predictor Variables for the Presence of Iceberg Pits
Revised Grand Banks Scour Catalogue

Stress Ratio Class Interval	Second-Order Predictor Variables	Third-Order Predictor Variables	Fourth-Order Predictor Variables
0			
1-10	Wave Height		
10-100	Tidal Amplitude	Grain Size Water Depth Seabed Aspect Iceberg Density	Iceberg Density Seabed Aspect Wave Height
100-1000	Iceberg Density	Tidal Amplitude Wave Height	
1000-10 000	Wave Height		

Table 6.5
"IF-THEN" Rules for Classified Iceberg Pit Densities
Revised Grand Banks Scour Catalogue

RULE 1 IF
Isobath = [50,90)
Tides = [10,55)
THEN
Craters = Absent 99.3%
Craters = 1-3.5 0.7%

RULE 2 IF
Isobath = [50,90)
Tides = [55,76]
THEN
Craters = Absent 94.0%
Craters = 1-3.5 6.0%

RULE 3 IF
Isobath = [90,150)
Iceberg = <1
THEN
Craters = Absent 100.0%

RULE 4 IF
Isobath = [90,150)
Iceberg = 1-2
Waveprd2 = [13.5,14)
THEN
Craters = Absent 100.0%

RULE 5 IF
Isobath = [90,150)
Iceberg = 1-2
Waveprd2 = [14,14.2)
THEN
Craters = Absent 69.6%
Craters = 1-3.5 30.4%

RULE 6 IF
Isobath = [90,150)
Iceberg = 1-2
Waveprd2 = [14.2,14.9]
THEN
Craters = Absent 99.1%
Craters = 1-3.5 0.9%

RULE 7 IF
Isobath = [90,150)
Iceberg = 2-3
THEN
Craters = Absent 86.2%
Craters = 1-3.5 12.8%
Craters = 5.0-12.0 1.1%

RULE 8 IF
Isobath = [90,150)
Iceberg = 3-4 to 5-6
Tides = [10,55)
THEN
Craters = Absent 90.1%
Craters = 1-3.5 9.8%
Craters = 5.0-12.0 0.1%

RULE 9 IF
Isobath = [90,150)
Iceberg = 3-4 to 5-6
Tides = [55,65)
THEN
Craters = Absent 61.2%
Craters = 1-3.5 36.7%
Craters = 3.5-5.0 2.0%

RULE 10 IF
Isobath = [90,150)
Iceberg = 3-4 to 5-6
Tides = [65,76]
THEN
Craters = Absent 84.2%
Craters = 1-3.5 14.2%
Craters = 3.5-5.0 1.7%

RULE 11 IF
Isobath = [90,150)
Iceberg = 6-7
THEN
Craters = Absent 42.9%
Craters = 1-3.5 57.1%

RULE 12 IF
Isobath = [150,200)
Grainsize = [0.01,0.104)
Wavehgt2 = [8.4,9.5)
THEN
Craters = Absent 100.0%

RULE 13 IF
Isobath = [150,200)
Grainsize = [0.01,0.104)
Wavehgt2 = [9.5,9.8)
THEN
Craters = Absent 74.2%
Craters = 1-3.5 25.8%

RULE 14 IF
Isobath = [150,200)
Grainsize = [0.01,0.104)
Wavehgt2 = [9.8,10.7]
THEN
Craters = Absent 100.0%

RULE 15 IF
Isobath = [150,200)
Grainsize = [0.104,0.233)
Tides = [10,34)
THEN
Craters = Absent 58.2%
Craters = 1-3.5 39.0%
Craters = 3.5-5.0 0.7%
Craters = 5.0-12.0 2.1%

RULE 16 IF
Isobath = [150,200)
Grainsize = [0.104,0.233)
Tides = [34,76]
Waveprd2 = [13.5,14.4)
THEN
Craters = Absent 94.4%
Craters = 1-3.5 5.6%

RULE 17 IF
Isobath = [150,200)
Grainsize = [0.104,0.233)
Tides = [34,76]
Waveprd2 = [14.4,14.6)
THEN
Craters = Absent 55.6%
Craters = 1-3.5 44.4%

RULE 18 IF
Isobath = [150,200)
Grainsize = [0.104,0.233)
Tides = [34,76]
Waveprd2 = [14.6,14.9]
THEN
Craters = Absent 96.6%
Craters = 1-3.5 3.4%

RULE 19 IF
Isobath = [150,200)
Grainsize = [0.233,0.308)
Waveprd2 = [13.5,14)
THEN
Craters = Absent 96.0%
Craters = 1-3.5 4.0%

RULE 20 IF
Isobath = [150,200)
Grainsize = [0.233,0.308)
Waveprd2 = [14,14.2)
THEN
Craters = Absent 44.8%
Craters = 1-3.5 31.0%
Craters = 3.5-5.0 13.8%
Craters = 5.0-12.0 10.3%

RULE 21 IF
Isobath = [150,200)
Grainsize = [0.233,0.308)
Waveprd2 = [14.2,14.6)
THEN
Craters = Absent 66.0%
Craters = 1-3.5 32.0%
Craters = 5.0-12.0 2.0%

RULE 22 IF
Isobath = [150,200)
Grainsize = [0.233,0.308)
Waveprd2 = [14.6,14.9]
THEN
Craters = Absent 96.2%
Craters = 1-3.5 3.8%

RULE 23 IF
Isobath = [150,200)
Grainsize = [0.308,1.347)
THEN
Craters = Absent 89.6%
Craters = 1-3.5 10.4%

RULE 24 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = <1 or 1-2
THEN
Craters = Absent 100.0%

RULE 25 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = 2-3
THEN
Craters = Absent 32.7%
Craters = 1-3.5 40.8%
Craters = 3.5-5.0 6.1%
Craters = 5.0-12.0 20.4%

RULE 26 IF
Isobath = [150,200)
Grainsize = [1.347,7.013)
Iceberg = 3-4 to 6-7
THEN
Craters = Absent 82.5%
Craters = 1-3.5 17.5%

RULE 27 IF
Isobath = [150,200)
Grainsize = [7.013,29.041]
Wavehgt2 = [8.4,9.1)
THEN
Craters = Absent 93.8%
Craters = 1-3.5 6.2%

RULE 28 IF
Isobath = [150,200)
Grainsize = [7.013,29.041]
Wavehgt2 = [9.1,9.5)
THEN
Craters = Absent 61.1%
Craters = 1-3.5 38.9%

RULE 29 IF
Isobath = [150,200)
Grainsize = [7.013,29.041]
Wavehgt2 = [9.5,10.5)
THEN
Craters = Absent 94.1%
Craters = 1-3.5 5.9%

RULE 30 IF
Isobath = [150,200)
Grainsize = [7.013,29.041]
Wavehgt2 = [10.5,10.6)
THEN
Craters = Absent 66.7%
Craters = 1-3.5 26.7%
Craters = 3.5-5.0 6.7%

RULE 31 IF
Isobath = [150,200)
Grainsize = [7.013,29.041]
Wavehgt2 = [10.6,10.7]
THEN
Craters = Absent 100.0%

RULE 32 IF
Isobath = [200,250)
Wavehgt2 = [8.4,9.1)
Aspect = No Aspect to 90-135
THEN
Craters = Absent 96.7%
Craters = 1-3.5 3.3%

RULE 33 IF
Isobath = [200,250)
Wavehgt2 = [8.4,9.1)
Aspect = 135-180
THEN
Craters = Absent 70.0%
Craters = 1-3.5 20.0%
Craters = 5.0-12.0 10.0%

RULE 34 IF
Isobath = [200,250)
Wavehgt2 = [8.4,9.1)
Aspect = 180-225 to 315-360
THEN
Craters = Absent 98.8%
Craters = 1-3.5 1.2%

RULE 35 IF
Isobath = [200,250)
Wavehgt2 = [9.1,9.8)
Curspeed = 0-5 or 5-10
Aspect = No Aspect
THEN
Craters = Absent 75.0%
Craters = 1-3.5 20.0%
Craters = 3.5-5.0 3.0%
Craters = 5.0-12.0 2.0%

RULE 36 IF
Isobath = [200,250)
Wavehgt2 = [9.1,9.8)
Curspeed = 0-5 or 5-10
Aspect = 0-45 to 315-360
THEN
Craters = Absent 97.9%
Craters = 1-3.5 2.1%

RULE 37 IF
Isobath = [200,250)
Wavehgt2 = [9.1,9.8)
Curspeed = 10-15 or 15-20
THEN
Craters = Absent 57.1%
Craters = 1-3.5 37.5%
Craters = 3.5-5.0 3.6%
Craters = 5.0-12.0 1.8%

RULE 38 IF
Isobath = [200,250)
Wavehgt2 = [9.8,10)
Transrate = Zero or 1-10
THEN
Craters = Absent 27.5%
Craters = 1-3.5 59.4%
Craters = 3.5-5.0 5.8%
Craters = 5.0-12.0 7.2%

RULE 39 IF
Isobath = [200,250)
Wavehgt2 = [9.8,10)
Transrate = 10-100 to 10000+
THEN
Craters = Absent 100.0%

RULE 40 IF
Isobath = [200,250)
Wavehgt2 = [10,10.3)
THEN
Craters = Absent 100.0%

RULE 41 IF
Isobath = [200,250)
Wavehgt2 = [10.3,10.6)
Transrate = Zero
THEN
Craters = Absent 26.7%
Craters = 1-3.5 69.5%
Craters = 3.5-5.0 1.9%
Craters = 5.0-12.0 1.9%

RULE 42 IF
Isobath = [200,250)
Wavehgt2 = [10.3,10.6)
Transrate = 1-10 to 10000+
THEN
Craters = Absent 100.0%

RULE 43 IF
Isobath = [200,250)
Wavehgt2 = [10.6,10.7]
THEN
Craters = Absent 83.3%
Craters = 1-3.5 16.7%

RULE 44 IF
Isobath = [250,500]
Grainsize = [0.01,0.39)
Waveprd2 = [13.5,14.2)
THEN
Craters = Absent 99.6%
Craters = 1-3.5 0.4%

RULE 45 IF
Isobath = [250,500]
Grainsize = [0.01,0.39)
Waveprd2 = [14.2,14.4)
THEN
Craters = Absent 79.2%
Craters = 1-3.5 16.7%
Craters = 3.5-5.0 4.2%

RULE 46 IF
Isobath = [250,500]
Grainsize = [0.01,0.39)
Waveprd2 = [14.4,14.9]
THEN
Craters = Absent 100.0%

RULE 47 IF
Isobath = [250,500]
Grainsize = [0.39,0.486)
THEN
Craters = Absent 44.1%
Craters = 1-3.5 50.8%
Craters = 3.5-5.0 3.4%
Craters = 5.0-12.0 1.7%

RULE 48 IF
Isobath = [250,500]
Grainsize = [0.486,29.041]
THEN
Craters = Absent 100.0%

Table 6.6
Predictor Variables for Classified Iceberg Pit Densities
Revised Grand Banks Scour Catalogue

Water Depth Interval (m)	Second-Order Predictor Variables	Third-Order Predictor Variables	Fourth-Order Predictor Variables
50-90	Tidal Amplitude		
90-150	Iceberg Density	Wave Period Tidal Amplitude	
150-200	Grain Size	Wave Height Tidal Amplitude Wave Period Iceberg Density	Wave Period
200-250	Wave Height	Seabed Aspect Current Speed Transport Rate	Seabed Aspect
250-500	Grain Size	Wave Period	

7. RISK ASSESSMENT

7.1 Methodology for Risk Assessment

One of the primary goals of this project has been to develop a framework for assessing the risk and the probability of occurrence of iceberg pits of various depths at various locations on the Grand Banks. Once developed, each individual component of the risk assessment framework could then be updated or improved as necessary.

There are several different ways in which the probability of occurrence of iceberg pits of various depths at a given location in the study area could be estimated. Two such approaches are outlined in Figure 7.1. In the first approach, shown on the left-hand side of Figure 7.1, the risk assessment process is based on seabed observations of ice-contact features. In the second approach, shown on the right-hand side of Figure 7.1, the process is based on observations of the presence of icebergs in the waters of the Grand Banks of Newfoundland. In both methods, available data are used as the basis for assessing the probability of a new iceberg pit forming at each particular location of interest.

Using seabed observations of ice-contact features, the empirical rules discussed in Section 6.0 of this report can be extended to form regional maps of the probability of observing an iceberg crater at any location in the study area. This process is discussed in more detail in Section 7.2. However, the population of ice-contact features observed at any given time on the seabed represents features formed over an extended time period, perhaps many thousands of years, and may include relict as well as recent features. In order to determine the rate at which new iceberg pits are formed on the seabed, and thus the risk to seabed structures, the observed population of iceberg pits must be separated into modern and relict populations and the probability of pit occurrence values adjusted for the age distribution of the observed pit population.

Pit age and the separation of iceberg craters into recent and relict populations have been discussed briefly in Sections 1.2, 2.0 and 3.5 of this report. Many of the previous studies related to the various iceberg scour databases have differentiated between relict and recent features, using both water depth and feature appearance assumptions to distinguish the two populations. It has previously been assumed that all ice-contact features found more than 200 m below the modern-day sea level represent relict features, based on limited observations of draft distributions of the contemporary iceberg population. Ice-contact features found in water depths shallower than 110 m have been assumed to represent recent features, based on estimates of the position of the late Wisconsinan low sea-level stand (see Section 4.3.1). The features found between 110 and 200 m have been assumed to include both relict features formed prior to the low sea-level stand and recent features formed after the shelf transgression. Only "fresh-appearing" features in this water depth range have been included in some portions of the Grand Banks Scour Catalogue (see Table 2.3).

Previous studies have also suggested that relict ice-contact features may have been formed at a time when the ambient icebergs were much larger than those that are currently present on the Grand Banks of Newfoundland. As a result, relict features may be larger and deeper than the modern population of ice scours. Thus, it may be possible to differentiate between modern and relict iceberg crater populations based on changes in pit dimensions with water depth.

The differences in pit width and pit depth for the shallow-water (less than 110 m) and deep-water (more than 110 m) iceberg pit populations are discussed in Sections 3.3 and 3.5 of this report. Trends in pit depth and pit width with increasing water depth are shown in Figure 3.11 and 3.12, respectively. These preliminary analyses indicate that the deep-water population of iceberg pits may be somewhat wider, although not deeper, than the shallow-water population. Weak trends in the data are also present, with both crater depth and width generally increasing with increasing water depth.

Due to many complicating factors, it is difficult to draw firm conclusions from these trends. Important factors include:

- the sample size is very small for the shallow-water population of iceberg pits, thus, confidence in some statistical values is relatively low;
- some pit observations may have been omitted from the GBSC in water depths greater than 110 m;
- the accuracy of pit width and depth measurements is unknown (Section 2.2.4); and
- seabed reworking may have led to infilling of older features, reducing the measured pit depth from the original depth of the feature when formed.

Finally, the presence of larger features in deeper waters may reflect an increase in iceberg size required to form ice-contact features in deeper waters, rather than the presence of relict features. Although this study has not indicated physical parameters that can be used to clearly differentiate between modern and relict iceberg pit populations, more detailed analyses of the existing data may clarify this issue.

The age distribution of the modern population of ice-contact features is also somewhat unclear. The sea level curve presented in Figure 4.8 indicates that current water levels on northeastern Grand Bank were essentially established on the order of 10 000 years B.P. However, recent studies suggest that the cold Labrador Current was not re-established in its current path until 5 000 to 2 500 years B.P. (Miller et al. in prep.). Previous to the re-establishment of the Labrador Current, there would have been no mechanism to transport icebergs southwards from their northern sources onto the Grand Banks. Thus, the modern population of iceberg pits can be assumed to have a maximum possible age of between 2 500 and 5 000 years.

This issue is again complicated by the effects of seabed mobility and sedimentary infilling, where, in areas of active sediment movement, pit features may be obliterated from the seabed record. The time frame over which significant infilling and degradation of pit features occurs must be assessed in order to establish the true time period reflected by the seabed record of ice scouring.

An alternative approach to determining the rate at which new iceberg pits form on the seabed is outlined on the right-hand side of Figure 7.1. In this second approach, the probability of observing an iceberg at the location of interest is assessed from available data. The methodology involved in such an assessment is described by Kelly (1996); his results for annual average iceberg densities on the Grand Banks of Newfoundland are presented in Figure 4.17 of this report.

In order to estimate the rate at which new pits are formed, the probability that a given iceberg will form a pit on the seabed must be assessed. This requires knowledge of both the physical dimensions (e.g., draft, height, width, length) of the icebergs present throughout the study area and the likelihood that an iceberg of known dimensions will create an iceberg pit at a given location. Measurements of iceberg dimensions, particularly draft, are extremely limited and are not available on a regional basis.

As summarized in Section 1.1 of this report, previous studies have postulated two possible mechanisms for iceberg pit formation. In the first mode, a grounded iceberg is subjected to oscillatory wave loading, probably during storm events. The wave loading leads to failure and perhaps liquefaction of the seabed surrounding and below the iceberg, forming a pit at the grounding site. In the second mode of pit formation, a sudden roll of an unstable iceberg leads to an increase in iceberg draft, with the iceberg impacting the seabed in a rotational manner. The rotating iceberg digs into the seabed, again causing soil failure or liquefaction and resulting in the formation of a seabed crater.

Estimating the probability that an iceberg of known dimensions will create an iceberg pit requires detailed knowledge of the physics of pit creation mechanisms as well as the wave and seabed conditions at each location of interest. Quantifying the risk of pitting from a given iceberg would entail the use of detailed numerical models including both hydrodynamic and geotechnical processes.

Once the rate of formation of new pits has been determined, the probability of occurrence for iceberg pits of specified depths can be assessed, if the depth distribution of newly-formed pits is known. Although the depth distribution of contemporary pits could be determined from the available measurements if the modern pit population could be effectively separated from the population of relict features, the accuracy of the pit depth measurements contained in the GBSC remains uncertain (see Section 2.2.4). Alternatively, depth-distribution information could be obtained through the use of numerical models of the pit creation process; again, this would require detailed information on the range of iceberg characteristics and the environmental conditions at each site of interest.

It is clear from this discussion that there are many sources of uncertainty in the risk assessment process. The work completed for this study has followed the approach outlined on the left-hand side of Figure 7.1, where the pit formation rate is based on seabed observations of ice-contact features. The focus of this study has been on determining the probability of observing an iceberg pit on a regional basis over the Grand Banks of Newfoundland, as described in the following section.

7.2 Probabilities of Finding Iceberg Pits

The empirical rules discussed in Section 6.0 of this report describe the relationships between the occurrence of iceberg pits on the seabed of the Grand Banks of Newfoundland and the various environmental parameters thought to influence the formation of iceberg pits. These rules have been developed from the existing database of crater observations, and reflect those combinations of conditions found over the surveyed regions of the seabed (see Figure 3.4). To determine the probability of observing an iceberg pit on a regional basis throughout the study area, the empirical rules must be extended to unsurveyed areas of the seabed.

To convert the "IF-THEN" rules given in Table 6.2 and Table 6.5 to regional probability of pit occurrence maps, the SPANS modelling language is used for mapping purposes. Each individual rule is converted to a mapping equation where the probability given in the "THEN" part of the rule is applied to all seabed areas meeting the criteria given in the "IF" part of the rule. For example, Rule 1 in Table 6.2 indicates that, for seabed areas where the water depth is in the range between 50 and 80 m and the tidal amplitude is between 10 and 55 cm, the probability of observing an iceberg crater on the seabed is 0.003. All areas of the seabed conforming to these water depth and tidal amplitude criteria are assigned the probability value of 0.003.

The resulting map showing the regional variations in the probability of observing an iceberg crater on the sea floor is given in Figure 7.2. This map indicates that the highest probabilities of finding an iceberg crater occur on northeastern Grand Bank, in Downing Basin and in the southern portions of Avalon Channel. The lowest probabilities of observing a pit feature occur in deeper waters, particularly in the western portions of the study area where few icebergs are found (compare with Figure 4.17).

The mapping procedure has been repeated for each of the three classes of pit densities described by the empirical rules presented in Table 6.5. The resulting maps are shown in Figure 7.3, Figure 7.4 and Figure 7.5, for 1.0 to 3.5 craters km^{-2}, 3.5 to 5.0 craters km^{-2}, and 5.0 to 12.0 craters km^{-2}, respectively. Again, the highest probabilities of finding iceberg craters, using classified pit densities, can be found over northeastern Grand Bank, in Downing Basin and in the southern portions of Avalon Channel. The highest densities of iceberg craters (Figure 7.5) are also found predominantly in these areas, with the lowest densities found in shallower waters on the bank tops.

In general, the probability of occurrence for each pit density class interval decreases as the pit density value increases; thus, for a given area, the probability of finding 5.0 to 12.0 craters km^{-2} is generally lower than the probability of occurrence of the 1.0 to 3.5 craters km^{-2} density class interval. An interesting exception to this trend is over a fairly extensive section of northeastern Grand Bank, where the probability of occurrence of the 5.0 to 12.0 craters km^{-2} class is higher than the value for the 3.5 to 5.0 craters km^{-2} density class.

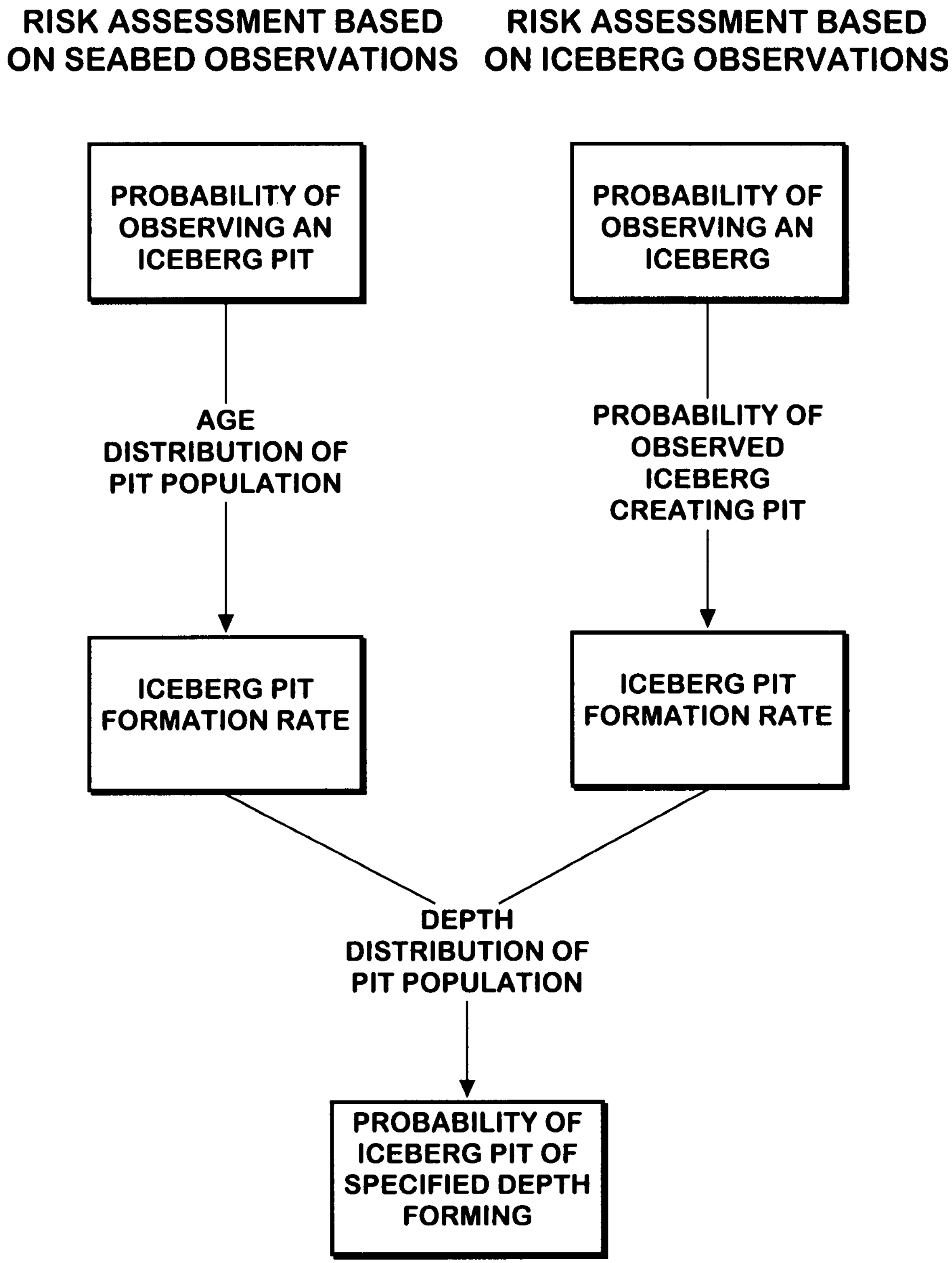


Figure 7.1 **Two approaches to estimating the probability of an iceberg pit of a specified depth forming at a given location.**

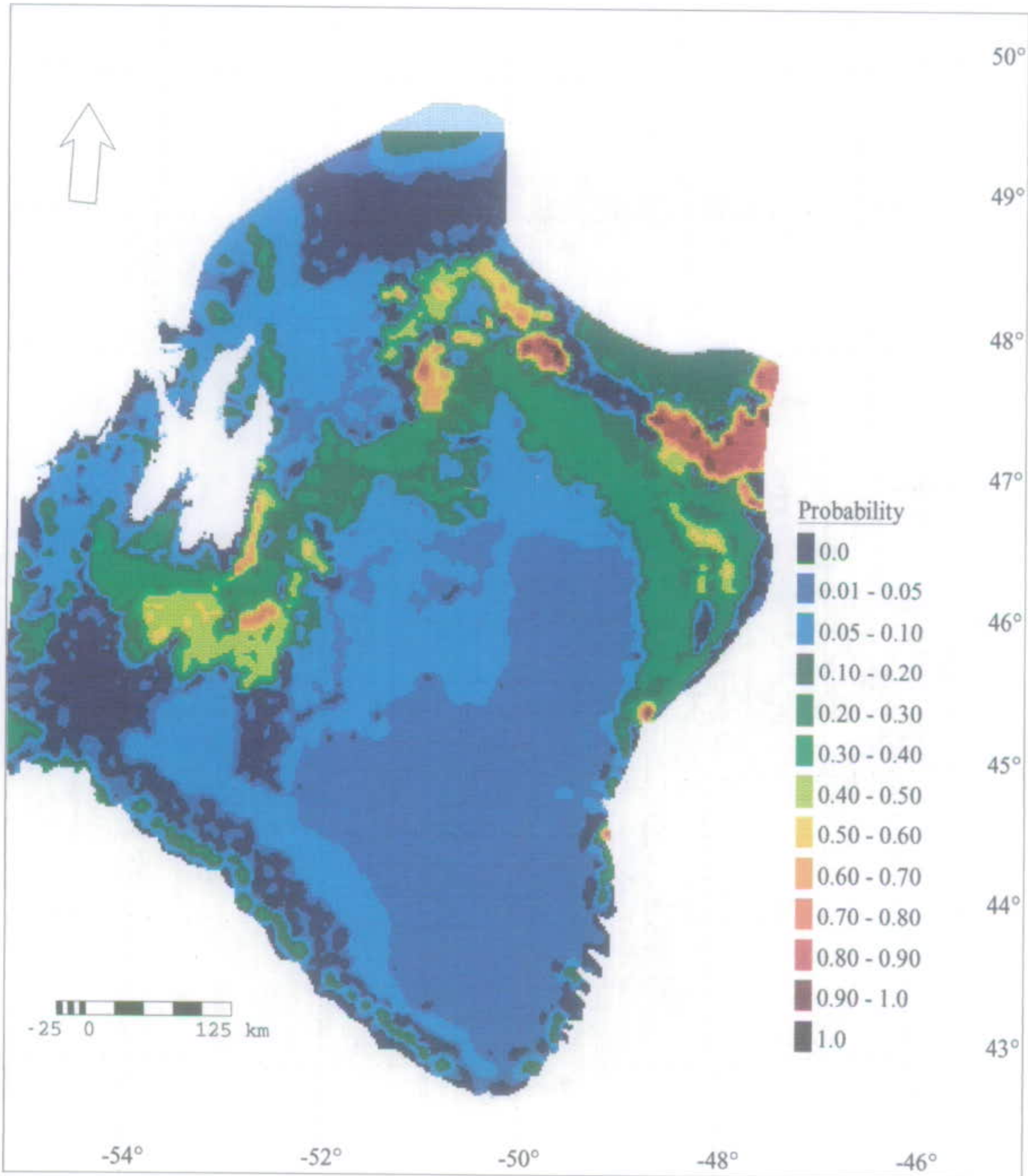


Figure 7.2 **Probability of observing an iceberg crater on the Grand Banks of Newfoundland.**

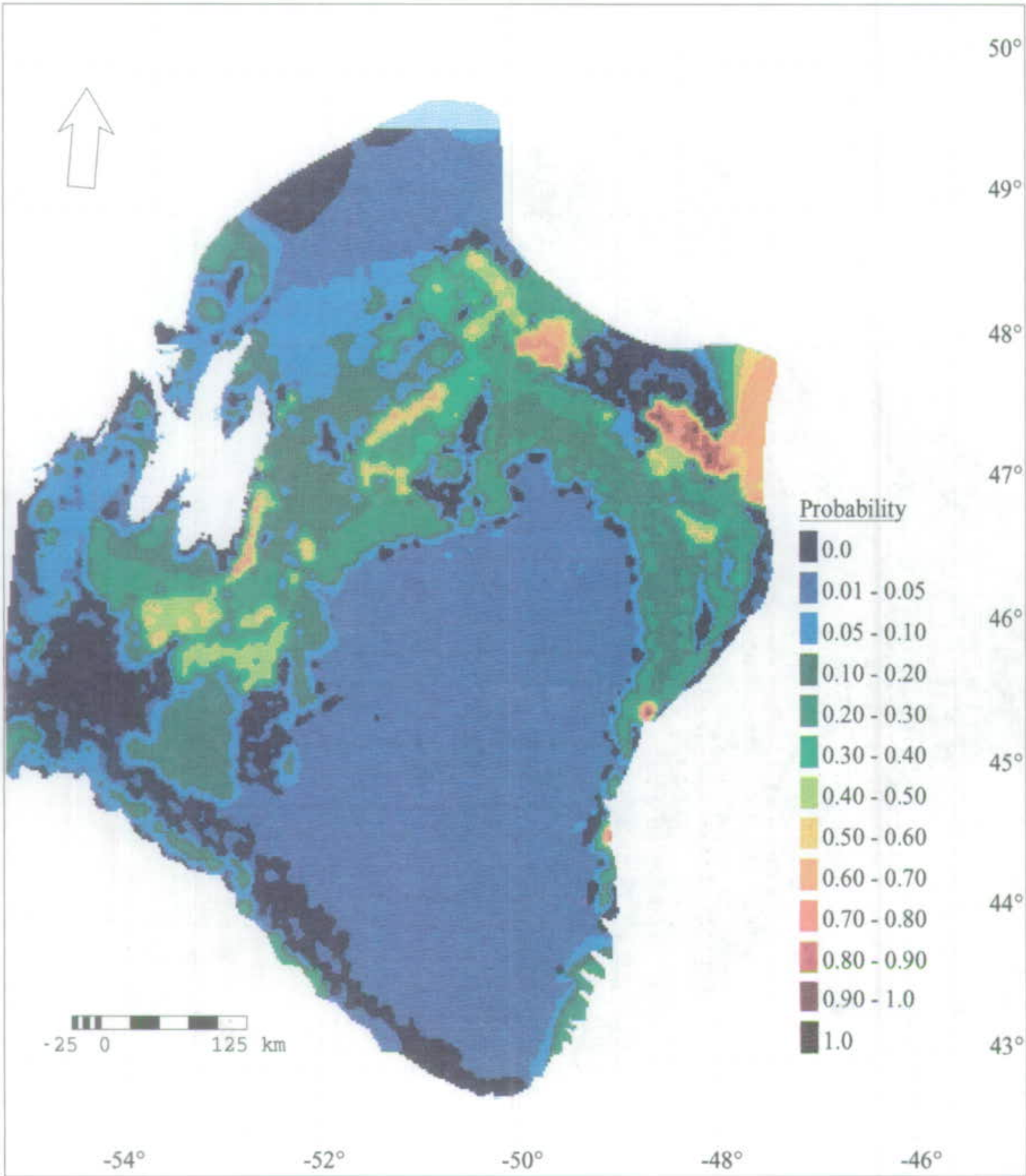


Figure 7.3 **Probability of observing 1 to 3.5 iceberg craters per km^2 on the Grand Banks of Newfoundland.**

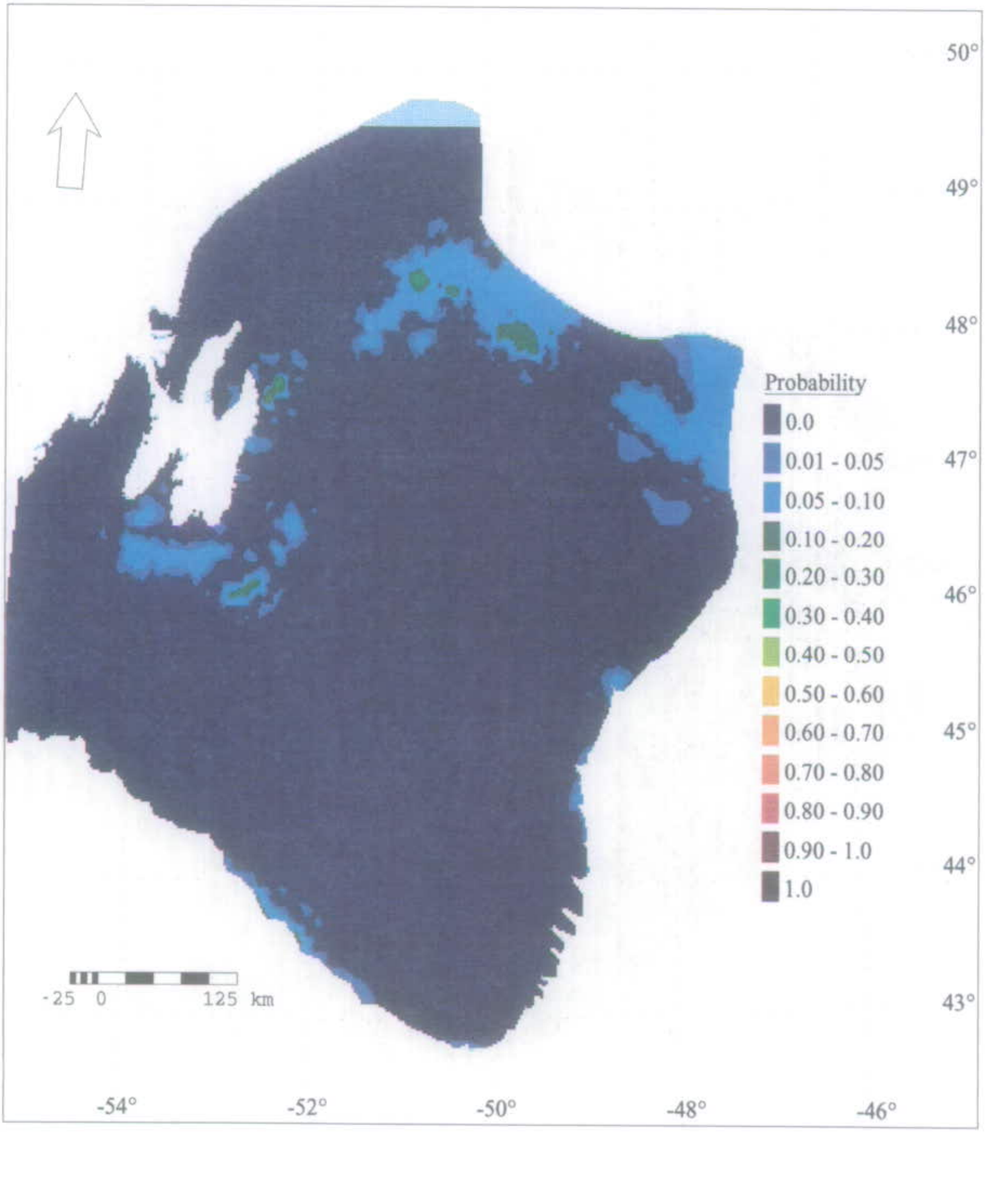


Figure 7.4 Probability of observing 3.5 to 5.0 iceberg craters per km^2 on the Grand Banks of Newfoundland.

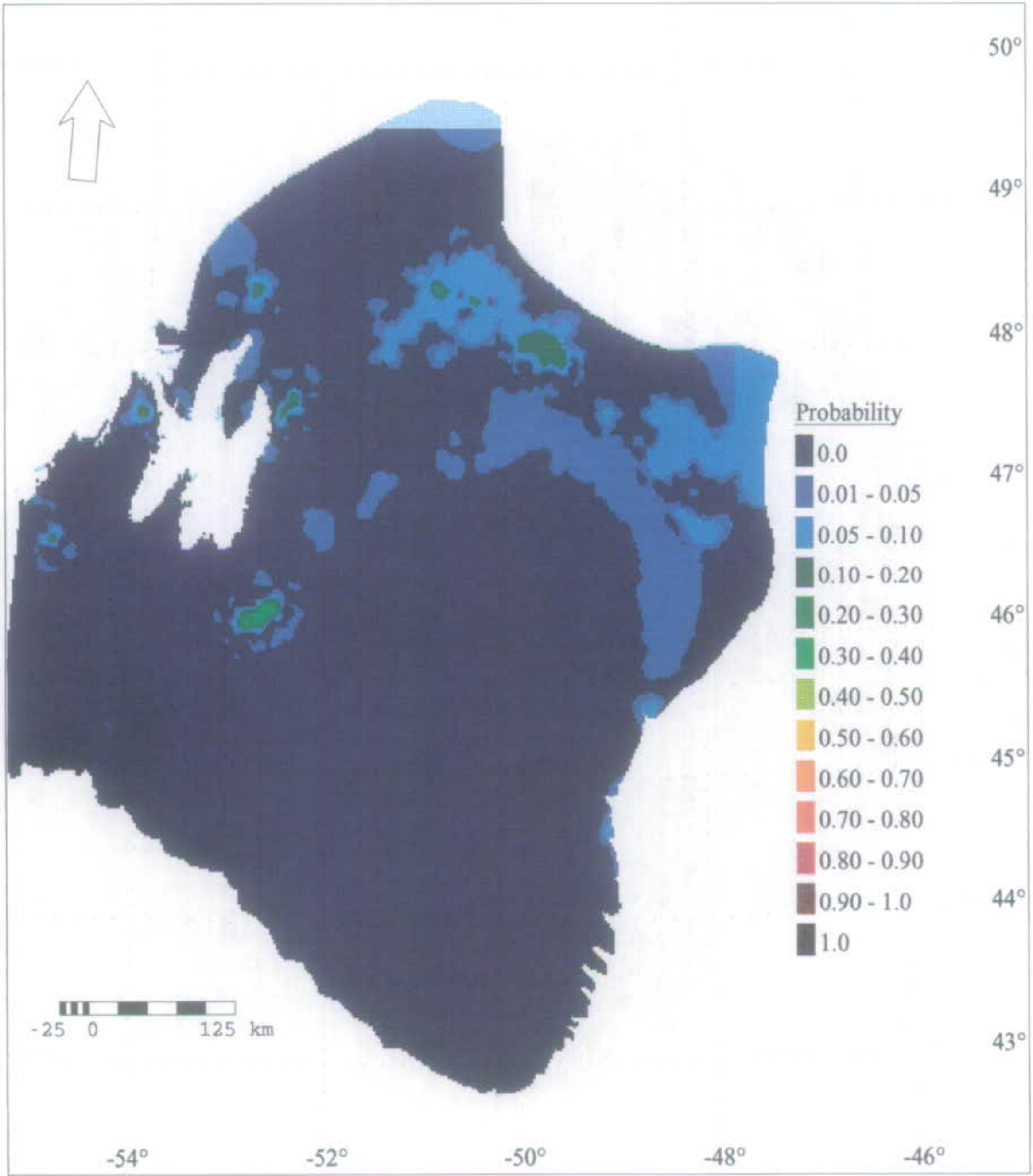


Figure 7.5 **Probability of observing 5.0 to 12.0 iceberg craters per km^2 on the Grand Banks of Newfoundland.**

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions from this Study

The purpose of the study described in this report was to examine the characteristics of iceberg pits on the Grand Banks of Newfoundland, and to provide an overall framework for the assessment of risk to seabed facilities from the iceberg pitting process. The study had these specific objectives:

- To collect and compile into consistent databases the relevant information on iceberg pits, their locations and observed physical characteristics, together with the relevant environmental parameters affecting pit formation and persistence on the Grand Banks of Newfoundland.
- To determine the statistical properties of the iceberg pit population.
- To define empirical rules relating the formation, persistence and physical characteristics of iceberg pits to the various environmental parameters.
- To estimate the probability of occurrence of iceberg pits of various depths at various locations on the Grand Banks of Newfoundland.

Each of these objectives are summarized in the following discussion.

Databases

For this study, information on iceberg pits, their locations and observed physical characteristics has been obtained from the Grand Banks Scour Catalogue, a digital database of seabed ice-contact features developed by Canadian Seabed Research Ltd. (1992) under previous funding from the Geological Survey of Canada. The Grand Banks Scour Catalogue represents a compilation of ice scour data from six distinct sources; these are described in Section 2.0 of this report.

The current project has focused on a detailed review of the various data sources and the individual parameters included in the GBSC, and has highlighted several limitations:

- Different methods have been used to identify ice-contact features in the different portions of the GBSC (see Table 2.3 and Section 2.2.2). Particularly important is the exclusion of some features from the database, based on the assumption that they represent relict features.

- The GBSC is inconsistent in format, with data entered differently in the various portions of the database (Section 2.2.1). These inconsistencies make the database difficult to use for data analysis purposes.

- Some ice-contact features appear to have been incorrectly classified as pits or scours (Section 2.2.2).

- Duplicate entries for the same feature may be present in the GBSC (Section 2.2.3).

- Information on feature dimensions is limited, with many blank fields in the database. The accuracy of dimension measurements (depth, width and length) is unclear (Section 2.2.4).

In order to define the areas of the seabed that have been surveyed and analysed for ice-contact features, a separate navigation database (NAVBASE) was developed by Canadian Seabed Research Ltd. (1992). The navigation database was only partially complete at the start of the current project, with several cruises missing from the database and others requiring assumptions to be made with respect to the extent of data analysis (Section 2.3.1). Considerable efforts have been devoted to the upgrading of the navigation database for use in this project.

The various environmental parameters included in the environmental factor database are described in Section 4.0 of this report. This database was developed to include many of the parameters thought to potentially influence the formation, characteristics and persistence of iceberg craters on the Grand Banks of Newfoundland. Parameters used in this study included water depth; tidal amplitude; speed and direction of the mean, depth-averaged currents; significant wave height and peak period for the two-year return period storm event; surficial geologic unit; grain size of the surficial sediments; sediment transport rate during the two-year storm event; a seabed mobility index developed specifically for this project; seabed aspect and iceberg density.

The limitations associated with the regional data coverage for the environmental parameters used in this project are discussed in Section 4.0. For some of the potentially-relevant environmental parameters, regional data were either unavailable (e.g., geotechnical parameters) or limited in quality and data coverage (e.g. seabed grain size). Nevertheless, the environmental database developed for this project represents a good first assessment of the regional variations in factors that affect iceberg pits on the Grand Banks of Newfoundland.

The iceberg pit database, navigation database and environmental factor databases have been incorporated into an iceberg pit geographic information system. The conversion of point data to regional maps and the calculation of spatial densities of iceberg craters (craters per square kilometre) are described in Section 5.0.

Properties of the Iceberg Pit Population

The statistical properties of the iceberg pit population are discussed in Section 3.0 of this report. The majority of iceberg craters have been recorded in three main areas: northeastern Grand Bank, Downing Basin and the southern portion of Avalon Channel. Very few pits have been observed in the shallower water regions on the bank tops. The majority of iceberg pit observations are associated with the wellsite surveys from the 1984 update to the Mobil Ice Scour Catalogue.

The median water depth in which iceberg pits have been observed is 164 m, with only 13% of the observed pits found in water depths shallower than 110 m. Of those craters with measured depth values, the median crater depth is 2.0 m. Although there is a weak trend for crater depths to increase with water depth, the errors associated with crater depth measurements are likely to be large. Crater widths show a median value of 60 m, again with width tending to increase with increasing water depth.

Separate statistical analyses were performed on the deep- and shallow-water crater populations, and on subsets of the crater population as defined by the geophysical analysis method. Although these preliminary analyses did not indicate strong differences in the observed physical characteristics of the various crater populations, further detailed analyses may lead to identification of distinct crater populations on the Grand Banks of Newfoundland.

Empirical Rules

The development of empirical rules relating the frequency of iceberg pit occurrence on the seabed to the various environmental parameters is described in Section 6.0 of this report. Empirical rules have been developed for both the presence and absence of iceberg pits, and for the classified crater densities shown in Figure 5.6. The entire data set of iceberg pits was used, with no distinctions between recent and relict features except for those already contained in the original databases (see Section 2.0).

For both sets of rules, water depth appears as the primary predictor of the presence of iceberg pits on the seabed. Second-order predictor variables include tidal amplitude, iceberg density, sediment grain size and wave height (Table 6.3 and Table 6.6). Several of the environmental parameters (e.g., sediment transport rate, seabed stress ratio, surficial geologic unit) are strongly linked to water depth and thus do not play an independent role in the prediction of the presence of iceberg pits on the seabed.

The relative importance of each predictor variable varies strongly between the various portions of the database. In general, clear trends relating changes in the pit occurrence rate to changes in the values of the predictor variables were not evident from the empirical rules. The effects of sedimentary infilling on the characteristics of the iceberg pit population were not discernible from the available data.

Probability of Occurrence of Iceberg Pits

The overall framework for assessing the risk to seabed structures from iceberg pitting events (i.e., the probability of occurrence of iceberg pits of various depths at various locations) on the Grand Banks of Newfoundland is summarized in Section 7.0. In order to complete a risk assessment based on seabed observations of iceberg pits, the age distribution of the observed pit population must be known. The depth distribution of the recent pit population is also required. Neither the age distribution of the observed pit population nor depth distribution of the recent pit population are known at this time.

The present project has focused on the methodology for predicting the probability of observing an iceberg pit on the seabed of the Grand Banks of Newfoundland. Regional maps showing the probability of finding an iceberg pit and the probabilities associated with each of the classified crater densities are shown in Figure 7.1 through Figure 7.4. These figures indicate that the highest probabilities of finding an iceberg crater occur on northeastern Grand Bank, in Downing Basin and in the southern portions of Avalon Channel. The lowest probabilities of observing a pit feature occur in deeper waters, particularly in the western portions of the study area.

8.2 Outstanding Issues

This study has led to the development of a framework for assessing the risk to seabed structures from the iceberg pitting process. Although the project has been relatively successful in describing the regional characteristics of the existing iceberg pit population and the probability of observing an iceberg pit on the seabed, several outstanding issues need further efforts before an accurate risk assessment can be completed. These include:

- The physical dimensions of the existing iceberg crater population must be accurately known.
- An effective methodology for discriminating between relict and recent iceberg pit features must be developed, particularly in water depths where both recent and relict features may be found.
- The age distribution of the modern iceberg crater population must be determined.

- The effects of seabed mobility and sedimentary infilling of iceberg craters must be assessed.

Alternatively, the risk assessment process could be approached from a knowledge of the regional distribution of icebergs under modern conditions. This approach requires:

- The regional variability in iceberg dimensions (width, length, draft, etc.).
- Detailed modelling of the pit formation process.
- The regional variability in the environmental parameters related to pit formation.
- The depth-distribution of the contemporary pit population.

8.3 Recommendations for Future Work

The two approaches to risk assessment described above each have limitations, based both on data limitations and limitations in our knowledge of the processes that affect the formation, characteristics and persistence of iceberg pits on the sea floor. Rather than choosing a single approach to risk assessment, it is recommended that two (or more) approaches be developed in parallel, allowing the assumptions inherent in each method to be independently assessed and compared.

The following specific tasks are recommended for future projects:

- The accuracy of the GBSC in terms of feature identification, duplicate features and feature dimensions should be determined. This could involve detailed intercomparison of selected seabed surveys, review of original geophysical records and use of new survey techniques such as swath bathymetry.
- The Grand Banks Scour Catalogue should be redesigned to remove inconsistencies from the database and to improve its ease of use for data analysis purposes.
- More detailed statistical analyses of the existing data may allow identification of distinct crater populations, and may provide insights into the separation of relict and recent iceberg pit populations. The iceberg pit geographic information system provides a convenient tool to further explore the spatial relationships between the various parameters.
- The navigation database should be improved to more accurately reflect those regions of each seabed survey actually analysed for ice-contact features. The

correct method for adjusting the crater densities for the actual area of seabed surveyed should also be determined (see Section 5.2).

- The resolution of the environmental database should be refined for the first- and second-order predictor variables. In particular, the resolution of the water depth and tidal amplitude databases could be relatively easily improved from existing data. Improving the sediment grain size database would require collection of additional seabed samples. Geotechnical parameters should be included in the environmental database if regional data become available in the future.

- The effects of seabed mobility and sedimentary infilling of iceberg craters should be assessed. This requires detailed modelling of the processes leading to infilling of seabed depressions (Davidson et al. 1988) plus collection of field data that could be used in the model calibration process (Davidson et al. 1991).

- The regional variability in iceberg dimensions should be examined. This would likely involve a combination of site-specific and regional studies of iceberg characteristics (Kelly 1996).

- The processes governing iceberg pit formation should continue to be investigated. Again, detailed numerical modelling in combination with the collection of appropriate field data is required. If adequate iceberg and environmental data are available, the depth distribution of the contemporary pit population could also be determined through the use of numerical models of the pit creation process.

- Separation of the observed iceberg pit population into recent and relict features and the age distribution of the recent iceberg pit population are perhaps the most difficult factors to assess. Investigation of alternative techniques to address these issues (see Section 7.1) should continue.

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